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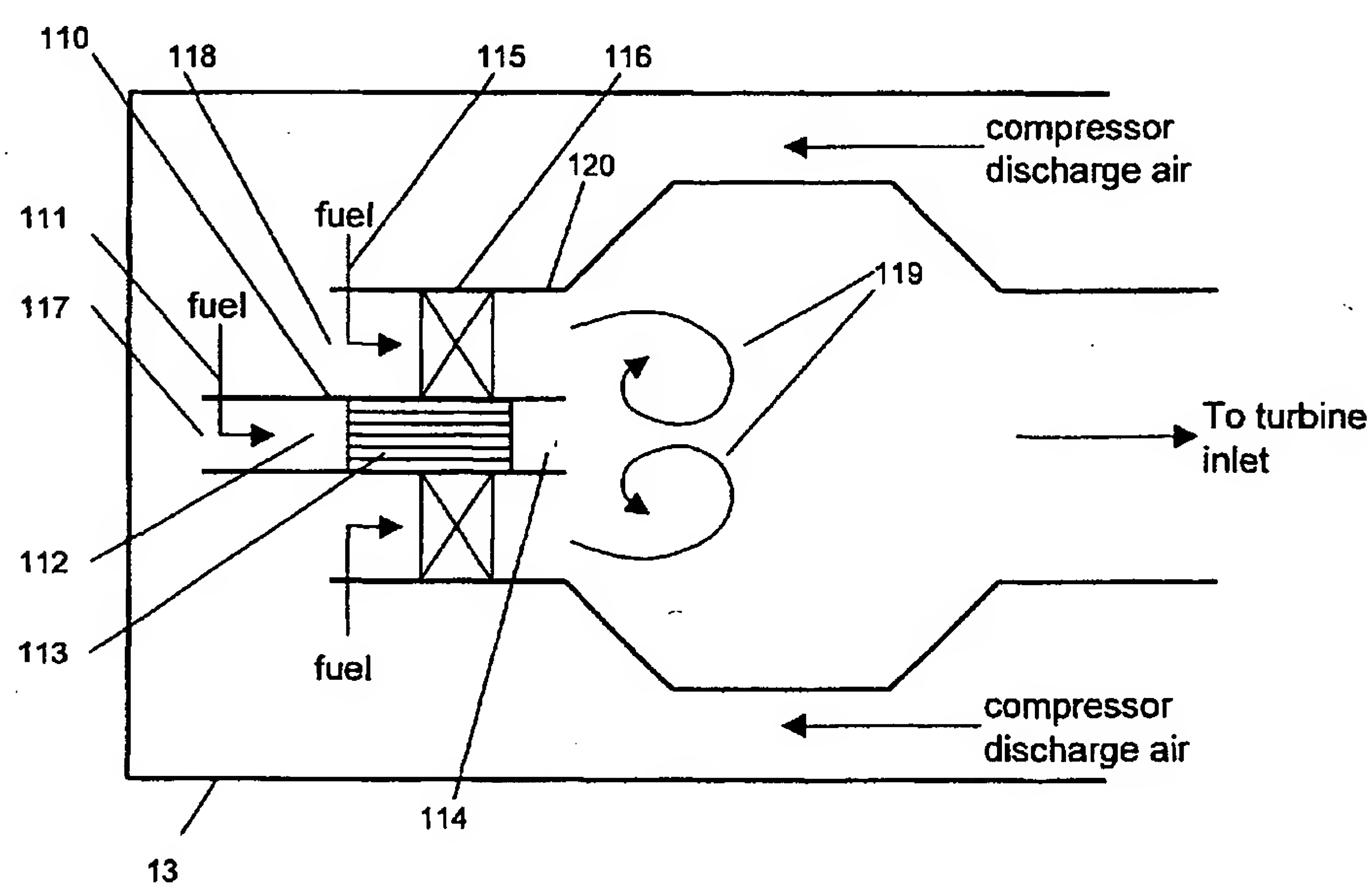

(57) Abstract: A combustor for a combustion system is described. The combustor includes an inlet region for receiving a compressor discharge air, and a pilot assembly (110) and main swirler-injector assembly (116) therein. The pilot assembly may include a pilot inlet region (112) for receiving at least a portion of the air, a catalyst (113) located downstream of the pilot region, a pilot fuel injec tor (111) for delivering pilot fuel upstream of the catalyst, and a pilot outlet region located downstream of the catalyst. The main swirler-injector assembly may include a main swirler-injector assembly inlet region and a main swirler-injector assembly fuel injector located downstream of the main swirler-injector assembly inlet region.

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CATALYTICALLY PILOTED COMBUSTION SYSTEM AND METHODS OF OPERATION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims benefit of earlier filed provisional application U.S. Serial No. 60/359,397, entitled "Catalytic Piloted Combustion," filed on February 22, 2002, and is incorporated herein by reference in its entirety.

BACKGROUND

1. Field of the Invention:

[0002] The present invention relates generally to methods and systems for reducing NO_x emissions in gas turbine engines, boilers, burners, and furnaces. More particularly, the present invention relates to methods and systems for reducing NO_x in gas turbine engines, boilers, burners, and furnaces using combustion piloted by a catalytic burner.

2. Description of Related Art:

[0003] One widely used device for the generation of electricity, power, and heat is the gas turbine engine. A typical gas turbine engine operates by ingesting air and compressing it using a rotating compressor. The pressurized air is passed through a chamber, or "combustor," wherein fuel is mixed with the air and burned. The high temperature exhaust of the combusted mixture expands across a rotating turbine, resulting in a torque created by the turbine. The turbine may then be coupled to an external load to harness the mechanical energy. Gas turbine engines are commonly used for electrical generators, and to power turbo-prop aircraft, pumps, compressors, and other devices that may benefit from rotational shaft power.

[0004] Boilers, burners, and furnaces also use combustion to generate heat for heating processes and generating high temperature steam and/or air. Air passes through a chamber, or "combustor," wherein fuel is mixed with the air and burned. The high temperature combustion of the fuel-air mixture is applied to heat exchangers or similar devices to transfer the heat from the combustion of the fuel and air to a desired medium.

[0005] Exhaust gases produced by combusting hydrocarbon and other fuels in typical combustion applications may contain undesirable emissions. For example, exhaust gases typically contain known pollutants such as nitric oxide (NO) and nitrogen dioxide (NO_2), which are frequently referred together as NO_x. Other emissions, for example, may include unburned hydrocarbons (UHC), carbon monoxide (CO), and particulates, such as carbon soot.

[0006] Nitrogen oxides are of particular concern because of their role in forming ground level smog and acid rain as well as depleting the stratospheric ozone. NO_x may be formed by several mechanisms in conventional combustion processes. First, "thermal NO_x," may form during the high temperature reaction of atmospheric oxygen with atmospheric nitrogen within the combustor, and particularly at adiabatic flame temperatures above about 2800° F. Second, "prompt NO_x," may form during the reaction of atmospheric nitrogen with hydrocarbon fuel fragments (CH_1), particularly under fuel-rich conditions. Finally, "fuel-bound NO_x," may form during the reaction of nitrogen released from a nitrogen-containing fuel with atmospheric oxygen, particularly under fuel-lean conditions. In typical combustors, atmospheric oxygen and nitrogen are readily available in the air that is mixed with the fuel and burned.

[0007] To limit NO_x formation, many modern combustors operate at uniformly fuel-lean conditions by using a lean premixed (LPM) system to reduce the formation of thermal and prompt NO_x. LPM systems operate at an equivalence ratio of less than 1.0, where the equivalence ratio is the ratio of the actual fuel-air ratio to the stoichiometric fuel-air ratio. An equivalence ratio greater than 1 indicates fuel rich conditions and a ratio less than 1 indicates fuel-lean conditions. Fuel-lean operation lowers adiabatic flame temperature, resulting in lower thermal NO_x formation, and lower prompt NO_x formation. The excess air used to achieve fuel-lean conditions reduces thermal NO_x formation by acting as a diluent to decrease peak flame temperatures. The excess air also decreases the concentration of hydrocarbons available to react with atmospheric nitrogen, thereby reducing the formation of prompt NO_x. The amount of excess air needed to reduce thermal and prompt NO_x formation may, however, cause the combustor to operate near its lean combustion limit, resulting in combustion instability and undesirable pressure dynamics. For example, at low equivalence ratios, the flame may be blown out. The lowest

equivalence ratio at which combustion can be sustained is known as the lean combustion limit. LPM flame stability can be improved by supplementing the main flame with hot vitiated air from a diffusion pilot flame to ensure that the main flame remains lit and stable at very lean conditions. Unfortunately, the added stability from the diffusion pilot flame comes at the cost of NO_x emissions formed within the diffusion pilot flame.

[0008] Therefore, methods and systems for gas turbine engines, burners, boilers, and furnaces are needed for reducing NO_x emissions while maintaining combustion stability in an LPM flame. Further, methods and systems for operating and controlling such devices with reduced NO_x emissions, including during the start-up, acceleration, and loading sequences, are needed.

BRIEF SUMMARY

[0009] According to one example of one aspect of the present invention, a combustor including a catalytic pilot is described. The combustor includes an inlet region for receiving compressor discharge air, and a pilot assembly and main swirler-injector assembly therein. The pilot assembly may include a pilot inlet region for receiving at least a portion of the air, a catalyst located downstream of the pilot inlet region, a pilot fuel injector for delivering pilot fuel upstream of the catalyst, and a pilot outlet region located downstream of the catalyst. The main swirler-injector assembly may include a main swirler-injector assembly inlet region for receiving at least a portion of the air, and a main swirler-injector assembly fuel injector located downstream of the main swirler-injector assembly inlet region. The combustor may further include a combustion zone located downstream of the main swirler-injector assembly fuel injector and downstream of the pilot assembly.

[0010] According to one example of another aspect of the present invention, a method for operating a combustor piloted by catalytic combustion pilot is described. The method may include delivering pilot fuel and air through the catalytic pilot, wherein the catalytic pilot includes a catalyst disposed upstream of a main swirler-injector assembly combustion zone. The method further includes adjusting at least one of the pilot fuel and the air delivered to the catalytic pilot to vary the catalyst exit conditions. For example, the

temperature, fuel composition, and the like exiting the catalytic pilot may be varied to reduce NO_x emissions of the system.

[0011] The present invention is better understood upon consideration of the detailed description below in conjunction with the accompanying drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The foregoing and other advantages of the invention will become apparent upon reading the following detailed description and upon reference to the drawings in which:

[0013] **Figure 1** illustrates an exemplary gas turbine system piloted by a catalytic combustor;

[0014] **Figure 2** illustrates an exemplary catalytic pilot configuration;

[0015] **Figure 3** illustrates an exemplary catalytic pilot configuration with two catalyst structures;

[0016] **Figure 4** illustrates an exemplary catalytic pilot configuration with a venturi throat mixer;

[0017] **Figure 5** illustrates an exemplary catalytic pilot configuration with two catalyst structures;

[0018] **Figure 6A** illustrates an exemplary catalytic pilot configuration with two inlet regions;

[0019] **Figure 6B** illustrates a partial cross-sectional view of the exemplary catalytic pilot configuration view of **Figure 6A** taken along line A-A;

[0020] **Figure 7** illustrates an exemplary catalytic pilot configuration with a post pilot fuel injector/burner;

[0021] **Figure 8** illustrates an exemplary catalytic pilot configuration with a post pilot mixing element;

[0022] **Figure 9** illustrates an exemplary catalytic pilot configuration with two air inlet regions;

[0023] **Figure 10** illustrates an exemplary catalytic pilot configuration with off-axis catalysts;

[0024] **Figure 11** illustrates an exemplary catalytic pilot configuration with an annular catalyst;

[0025] **Figure 12** illustrates an exemplary graph of speed, load, fuel flow, and compressor discharge temperature versus time for an exemplary control strategy for a combustor having a catalytic pilot;

[0026] **Figure 13** illustrates a diagram comparing an exemplary combustion system piloted by a catalytic combustor with and without an inlet duct burner;

[0027] **Figure 14** illustrates a diagram comparing an exemplary combustion system with and without a pre-heater;

[0028] **Figure 15** illustrates a graph comparing NO_x emissions in exemplary systems with a catalytic pilot and a diffusion flame pilot;

[0029] **Figure 16** illustrates a graph of NO_x emissions versus pilot equivalence ratio of various pilot configurations;

[0030] **Figure 17** illustrate a graph of pilot exit gas temperature versus pilot equivalence ratio;

[0031] **Figure 18** illustrates a graph of the dynamic pressure (RMS) versus the overall equivalence ratio of various pilot configurations; and

[0032] **Figure 19** illustrates an exemplary graph of catalytic pilot exit gas temperature versus pilot fuel-air ratio for different catalysts.

DETAILED DESCRIPTION OF THE INVENTION

[0033] The following description is presented to enable any person skilled in the art to make and use the invention. Descriptions of specific materials, techniques, and

applications are provided only as examples. Various modifications to the examples described herein will be readily apparent to those skilled in the art, and the general principles defined herein may be applied to other examples and applications without departing from the spirit and scope of the invention. Thus, the present invention is not intended to be limited to the examples described and shown, but is to be accorded the widest scope consistent with the principles and features disclosed.

[0034] Various aspects of the present invention include the design, application, and control of a combustion system including catalytic combustion in place of a conventional diffusion pilot flame to improve LPM flame stability and decrease NO_x emissions. An exemplary catalytic pilot may reduce or prevent the formation of thermal NO_x typically generated by diffusion flame pilots because the catalyst generally operates below temperatures where thermal NO_x forms. Further, a catalytic pilot may reduce or prevent the formation of prompt NO_x because the catalyst may operate under fuel-lean conditions. Further, an exemplary catalytic pilot system may provide desired pilot exit conditions, e.g., exit temperature, fuel/air mixtures, and the like, to improve LPM flame stability without adding undesirable NO_x emissions generated by typical diffusion flame pilots.

[0035] Broadly speaking, combustion may be defined as the exothermic reaction of fuel and an oxidant. Combustion takes place in many forms, two of which are flame combustion and spontaneous combustion. Stable flame combustion of a mixture of fuel and air generally occurs only when the mixture of fuel and air are within the flammable limits based on, for example, equivalence ratios, pressure, temperature, and the like. Flame combustion may further be divided into two main classes – diffusion flame and premixed flame combustion. In a diffusion flame, the rate of mixing between the fuel and oxidant to generate a flammable mixture is slow so that the overall rate of combustion is limited by the mixing rate. In a diffusion flame, fuel is fed in a stream into the combustion zone and combustion takes place in the boundary layer between a fuel-rich core and the oxygen-rich surrounding. Oxidation rate is limited by the rate of diffusion of fuel from the core to this boundary layer. Flame temperatures are very high as combustion takes place at near-stoichiometric conditions. In a premixed flame, the fuel and oxidant are rapidly mixed together prior to combustion, for example, with a swirler, turbulent mixing tube, or the like such that the overall rate of combustion is based on the subsequent chemical reaction rates

and other macroscopic system parameters such as pressure, temperature, equivalence ratio, heat conduction, and the like. A specific sub-class of a premixed flame is a lean premixed (LPM) flame whereby the flammable mixture is fuel lean to result in low flame temperatures and minimal thermal NO_x formation. In typical LPM combustion systems, an ignition source such as a hot surface or an electric spark, is generally used to initiate the flame to combust the flammable mixture.

[0036] Spontaneous combustion, sometimes referred to as homogeneous combustion, spontaneous ignition, or auto-ignition, is a form of combustion wherein the mixture of fuel and oxidant undergoes a chemical reaction which leads to the rapid evolution of heat in the absence of any concentrated source of ignition such as a flame or spark. Spontaneous combustion that is initiated by a catalytic reaction is generally referred to as catalytic combustion. The description herein of exemplary catalytic pilot assemblies involves two categories of catalytic combustion. In one category, the catalyst is designed such that all the fuel that passes through the catalyst initiates the chemical reaction and is fully combusted. The gas exiting the catalyst substrate is therefore predominately vitiated air, i.e., containing combustion products of CO_2 and H_2O. In a second category of catalytic combustion, the catalyst is designed such that only a portion of the fuel (approximately 10 to 75%) that passes through the catalytic substrate is combusted. The gas exiting the catalyst substrate is a mixture of vitiated air and heated fuel.

[0037] The catalytic pilot is desirably controlled to produce exit conditions desired to sufficiently stabilize the LPM flame and reduce NO_x emissions. Once catalyst combustion, or light-off has been established with the catalytic pilot, the catalytic pilot may combust or convert approximately 10 to 100% of the fuel delivered to the catalytic pilot. The conversion of fuel will generally be a function of the catalyst design and operating conditions for a particular combustion system. The level of conversion should be sufficient to generate the pilot exit conditions desired to stabilize the LPM flame. In the case where the catalyst converts 100% of the pilot fuel, the exit gas is composed solely of hot vitiated air. Therefore, it is desirable that the catalyst exit gas temperature is sufficiently high to stabilize the LPM flame, but not excessively high where thermal NO_x may form.

[0038] In the case where the catalyst converts less than 100% of the pilot fuel, the catalyst exit gas is composed of hot uncombusted fuel and vitiated air. In this instance,

characteristics of the catalyst exit gas mixture that may be varied include the exit temperature, ignition delay time, and adiabatic combustion temperature. The catalyst exit characteristics are desirably within a range that ensures LPM flame stability and minimal NO_x formation during operation.

[0039] The following description includes numerous pilot configurations for systems where the catalyst converts 100% of the pilot fuel and/or less than 100% of the pilot fuel. The various pilot configurations may be advantageously employed to vary the pilot exit conditions and to stabilize the main flame in a variety of combustion systems.

[0040] **Exemplary Catalytic Pilot Configurations**

[0041] **Figure 1** illustrates an exemplary gas turbine system piloted by catalytic combustion. Compressor 11 ingests ambient air 12 through a compressor bellmouth and compresses the air to a higher pressure. The compressed air is driven, at least in part, through the combustor 13 and through the drive turbine 14. A portion of compressed air is delivered to the burner(s) of combustor 13 through an air line or the like. Fuel is delivered to the swirler-injector assembly(s) of combustor 13 via a fuel line or the like. Combustor 13 includes a catalytic pilot (see **Figure 2**) for stabilizing the LPM flame of a main swirler-injector assembly disposed within combustor 13. The combustor 13 combusts the air and fuel to produce a hot high velocity gas stream that flows through turbine 14. The hot high velocity gas stream provides power to drive turbine 14 and the load 15. Load 15 may be, for example, a generator or the like. The hot gases are then discharged from the turbine 14 via an exhaust line or the like.

[0042] The exemplary gas turbine system of **Figure 1** is illustrative only, and it should be understood that combustor 13 may be included in other combustion systems. For example, combustor 13 piloted by a catalytic pilot may be included in a boiler, burner, furnace, and the like as will be recognized by those skilled in the art.

[0043] Referring to **Figure 2** in conjunction with **Figure 1**, a more detailed view of combustor 13 and an exemplary configuration of an LPM combustor piloted by a catalytic combustor is illustrated. The catalytic pilot 110 of this example includes an air inlet 117 for receiving a portion of the compressor discharge air. The catalytic pilot 110 further includes at least one catalyst fuel injector 111 for introducing fuel to the catalytic pilot 110.

A fuel-air mixing region 112 is located generally downstream of the fuel injector 111 and air inlet 117. A catalyst 113 is located downstream of the fuel-air mixing region 112 and a pilot outlet region 114 is located downstream of the catalyst 113.

[0044] Fuel injector 111 injects pilot fuel into the air stream entering pilot inlet 117. The fuel and air may mix in fuel-air mixing region 112. The mixture of fuel and air pass through catalyst 113 where at least a portion of the fuel and air combust and exits the pilot 110 through catalyst exit region 114 at a higher temperature. The hot fuel-vitiated air mixture exiting the catalyst 113 may spontaneously combust within the catalyst exit region 114 to produce predominately hot vitiated air exiting pilot 110. Alternatively, exit region 114 may be sufficiently small such that spontaneous combustion of the fuel and air does not fully occur such that fuel and hot vitiated air exit the catalytic pilot 110.

[0045] The main swirler-injector assembly 120 receives a portion of the compressor discharge air at location 118. The main swirler-injector assembly 120 generally includes at least one main fuel injector 115 and a fuel-air-mixing region or element 116, such as a typical swirler or the like. The main fuel may be mixed with air by mixing element 116 upstream of the re-circulation zone 119 (often referred to as the combustion zone). The catalytic pilot fuel 111 is at least partially combusted by catalyst 113 to generate hot gas exiting the catalyst 113 into the re-circulation zone 119. The hot vitiated gas mixes with the LPM fuel-air mixture in the combustion or re-circulation region 119 where the balance of combustion takes place to achieve a desired flame temperature.

[0046] The exit gas from the catalytic pilot 110 may be controlled, for example, by varying the pilot fuel 111 and/or intake air at 117, to stabilize the LPM flame in the re-circulation zone 119 with reduced formation of NO_x emissions. For example, a portion of the compressed air from the compressor may be delivered to the pilot assembly 110 through a pilot air-line (not shown). The amount of compressed air, which is branched off, may be adjusted by controlling a valve or the like. Similarly, pilot fuel 111 may be delivered to the catalytic pilot 110 of the combustor through a pilot fuel line. A valve or the like may be provided to control the amount of pilot fuel 111 delivered to the catalytic pilot 110. Desired amounts of air may be delivered to the mixing region 112 and mixed with the pilot fuel 111 to vary the exit conditions of the catalytic pilot 110. The desired fuel-air mixture may be delivered to the catalyst 113 to undergo a catalytic reaction and

delivered from the catalyst 113 to the combustion chamber, i.e., re-circulation zone 119 to support the main swirler-injector assembly flame.

[0047] With continued reference to **Figure 2** various illustrative design considerations and exemplary operating methods for a catalytic pilot will be described. The exemplary catalytic pilot generally includes four main components: (i) a fuel injector 111 for introducing fuel to the catalytic pilot; (ii) a fuel-air mixing region 112 to mix the fuel and air; (iii) a catalyst 113 to at least partially combust the fuel-air mixture; and (iv) a catalyst exit region 114 wherein the hot fuel-air mixture exits the catalytic pilot.

[0048] The fuel injector 111 injects pilot fuel into the flow path of air upstream of catalyst 113. The fuel injector 111 may include various fuel lines and fuel valves for modulating pilot fuel delivery. The fuel valve may be controlled based on a schedule of fuel flow or the like. Further, the fuel may be injected into the catalytic pilot by any suitable method. For example, fuel may be injected radially inward from a fuel manifold around the outer diameter of the catalytic pilot or radially outward from a manifold located in the flow path centerline of the catalytic pilot. The fuel may also be injected axially against or with the air flow direction from a radial fuel peg or injected perpendicular to the air flow direction from a radial fuel peg.

[0049] The catalytic pilot desirably includes a fuel-air mixing region 112 located within the catalytic pilot and located upstream of catalyst 113. The fuel-air mixing region 112 may include a sufficiently long mixing "tube" or region for the fuel and air to effectively diffuse together. The degree of mixing depends, at least in part, on the particular application as well as various design considerations for the particular catalyst and/or combustor. The fuel and air may also be mixed by a static mixer, such as a swirler (axial or radial) or any other device that generates turbulence and/or shear within the flow path. Other suitable methods known in the art for mixing the fuel and air may be used such as passing the fuel and air through the throat of a venturi mixer or the like.

[0050] The catalyst 113 may include various chemicals imparted on a suitable structure such that as the fuel and air mixture pass through catalyst 113 a portion or all of the fuel and air react. The structure and materials of catalyst 113 may generally include any suitable catalyst material and structure for catalytic combustion. Further, any number

of catalyst stages, as well as catalyst structures disposed in parallel, are contemplated within an exemplary catalytic pilot design. Depending on the particular application, specific catalyst designs may be varied to achieve a desired catalyst light-off temperature (LOT), defined as the temperature at which the fuel begins to react on the catalyst, a preferred conversion of the hydrocarbon fuel through the catalyst, and a preferred temperature exiting the catalyst in a system to stabilize the LPM flame over a desired operating range of the gas turbine engine.

[0051] In some exemplary systems it may be desired that the catalyst have sufficient activity to support catalytic combustion, i.e., achieve LOT, at part load conditions where the compressor discharge temperature that feeds the catalyst inlet is very low, e.g., less than approximately 350°C and between approximately 150 and 350°C. In one exemplary catalyst design, the catalyst may include a monolithic structure with all or portions of channels therein coated with dispersed precious metal to provide sufficient catalytic activity for light-off between about 150 and 350°C. Further, employing features that reduce the heat transfer rate without inhibiting the catalyst's surface activity rate may lower the catalyst light-off temperature (LOT). Examples of such characteristics include larger channel structures, channel structures with low heat transfer coefficients, reduced velocity of the fuel-air mixture within the monolith structure, special treatments to the inlet edge of the catalyst, or the like. Various exemplary catalyst characteristics are described, for example, in U.S. Pat. No. 5,183,401 to Dalla Betta et al., U.S. Pat. No. 5,232,357 to Dalla Betta et al., U.S. Pat. No. 5,248,251 to Dalla Betta et al, U.S. Pat. No. 5,250,489 to Dalla Betta et al., U.S. Pat. No. 5,259,754 to Dalla Betta et al., U.S. Pat. No. 5,512,250 to Dalla Betta et al., all of which are incorporated herein by reference in their entirety.

[0052] In other exemplary systems, external heat sources may be employed such as electrically heating the monolithic structure or preheating the air entering the catalyst to effectively cause the catalyst to combust fuel at lower compressor discharge temperatures. Electrically heating the catalyst monolith structure is described, for example, in U.S. Patent No. 6,109,018 to Rostrup-Nielsen, et al., which is incorporated herein by reference in its entirety.

[0053] In a multi-staged pilot catalyst system, it is preferred to limit these characteristics, i.e., to reduce the LOT, to the inlet or first stage catalyst. The second stage

catalysts may have higher LOT because they will receive generally higher temperature fuel-air mixtures exiting the first stage catalyst. The individual catalyst monoliths making-up the balance of the catalyst system may have, for example, the characteristics described by the previously cited U.S. Patents.

[0054] The catalyst exit region 114 includes the region located adjacent and downstream of the exit face of catalyst 113. The exit region 114 may be adjusted to achieve a desired exit temperature, fuel-air composition, and/or mixing effect in the combustor. For example, the exit region 114 may have a minimal or zero volume such that the catalyst exit temperature and gas composition (fuel and vitiated air or only vitiated air) does not change prior to entering the LPM re-circulation zone 119. Alternatively, the catalyst exit region 114 may have a sufficient volume such that the catalyst exit gas composition may spontaneously combust therein and supply high temperature vitiated air to the LPM re-circulation zone 119. For example, the vitiated gas temperature may vary from approximately 1100 to 1600°C to support the LMP flame, but the preferred range is approximately 1300 to 1400°C.

[0055] The catalyst exit region 114 may include a device such as a swirler to enhance the mixing of the catalyst exit gas in the LPM re-circulation zone 119. Further, the catalyst exit region 114 may include a device such as a fuel injector to add fuel to the hot vitiated air exiting the catalyst. The device may introduce fuel radially inward from the outer diameter or radially outward from the centerline. Such a device could also act as a diffusion flame to stabilize the LPM combustion flame during the engine start-up sequence before the compressor discharge temperature (CDT) air is hot enough to sustain catalyst combustion in the catalytic pilot, i.e., before catalyst light-off.

[0056] Additional exemplary catalytic pilot configurations are illustrated in **Figures 3-11**. It should be recognized, however, that the following examples are illustrative only and are not intended to be limiting. Certain exemplary designs may provide advantages over other designs depending on, for example, the particular application or design constraints of the system and desired catalytic pilot exit conditions.

[0057] In another exemplary catalytic pilot system, the catalytic pilot includes two or more catalyst stages as illustrated in **Figure 3**. In this instance, the combustor 33 of

Figure 3 is similar to that of **Figure 2** except that catalytic pilot 310 includes a first stage catalyst 313a and a second stage catalyst 313b located in series along the flow path. The first stage catalyst 313a may be designed to react with a rich low temperature fuel-air mixture and subsequent catalyst stages designed to react with leaner higher temperature fuel-air mixtures.

[0058] In particular, the catalyst fuel injector 311 injects fuel, which mixes with the incoming pilot air 317 in the pilot-mixing region 312. The pilot fuel is partially combusted by the first stage catalyst 313a to generate a hot fuel and at least partially vitiated air mixture. The higher temperature and leaner fuel-air mixture exiting first stage catalyst 313a enters second stage catalyst 313b. The second stage catalyst 313b may be advantageously designed to react with the higher temperature leaner fuel-air mixtures than the first stage catalyst 313a. The hot fuel-vitiated air mixture exiting the second stage catalyst 313b may spontaneously combust within the catalyst exit region 314, or exit region 314 may be sufficiently small such that spontaneous combustion does not fully occur. The high temperature gases exiting the catalytic pilot mix with the main swirler-injector assembly gases in the re-circulation zone 319 to stabilize the LPM flame as previously described.

[0059] **Figure 4** illustrates a cross-sectional view of an exemplary catalytic pilot configuration including a venturi throat mixer at the air inlet of the catalytic pilot. In this example, fuel is injected radially inward towards the central axis A-A from the outer walls 401 as illustrated by the arrows. The fuel is injected at the throat 402 of a venturi mixer such that compressor discharge air flowing through the throat 402 is mixed with the injected fuel within or near the venturi throat 402. The venturi throat 402 provides a suitable structure for mixing the fuel and air upstream of the catalyst 403. The pilot fuel may be introduced through one or more fuel lines 406 that may include controllable fuel valves (not shown) to modulate or adjust the fuel delivered to the pilot based on a pre-computed fuel schedule or the like.

[0060] The fuel-air mixture passes through catalyst 403 to generate a hot mixture of fuel and vitiated air that may homogeneously combust within the catalyst exit region 404 thereby further increasing the exit temperature of the catalytic pilot. Main swirler-injector assembly fuel may be delivered through main fuel line 409 and emerge in the combustion

or re-circulation zone 405 located downstream of exit region 404. The high temperature vitiated air emerging from exit region 404 mixes with main fuel from main swirler-injector assembly 408 in the re-circulation zone 405 to support combustion of the LPM flame. The particular catalytic pilot design and configuration shown in **Figure 4** generally provides a low cost method of integrating a catalytic pilot with an LPM swirler-injector assembly because a simple fuel injection mixing device is coupled with a single stage catalyst. Further, this example provides a simple, low-pressure drop fuel injection/mixing design through the venturi throat mixer.

[0061] **Figure 5** illustrates a cross-sectional view of another exemplary catalytic pilot configuration. In this example, the catalytic pilot includes a first annular catalyst stage 502 and second catalyst stage 504. The catalytic pilot is configured to reduce the velocity of the fuel-air mixture in the first catalyst stage 502 to reduce the light-off temperature of the first catalyst stage 502. The fuel-air mixture exiting the first catalyst stage 502 is heated by at least a partial reaction of fuel and air such that subsequent catalyst stages, i.e., catalyst stage 504, may be designed to react with leaner higher temperature fuel-air mixtures than the first stage catalyst 502.

[0062] Compressor discharge air and pilot fuel are mixed in an annular region disposed around the catalytic pilot. Compressor discharge air "WA" flows in through mixing region 501, which may include a swirler or the like as well as fuel pegs or the like for introducing pilot fuel from fuel line 506 to aid in facilitating the mixing of the pilot fuel and air. The fuel and air mixture pass over annular catalyst 502 located downstream of mixing region 501. The catalyst reacts with the fuel-air mixture, and the gases emerging from the first catalyst stage converge into a cylindrical region 503 at a higher temperature. In this example, the cross-section area of region 503 (viewed along axis A-A) may be significantly smaller than the cross-sectional area of mixing region 501 (viewed along the flow path), such that the velocity through mixing region 501 would be significantly less that the velocity through region 503. The leaner fuel-air mixture exiting first stage catalyst 502 therefore passes across second catalyst stage 504 located downstream of region 503 at a higher temperature and velocity. The second catalyst stage 504 may be advantageously designed to perform with at least one of a higher inlet temperature, higher velocity, and leaner fuel-air mixture than the first stage catalyst 502.

[0063] The hot fuel-vitiated air mixture exiting the second stage catalyst 504 may homogeneously combust within the catalyst exit region 505 depending on the length or volume of the exit region 505. The high temperature vitiated air exiting the pilot mixes with the main swirler-injector assembly 508 gases in the re-circulation zone 506 to stabilize the LPM flame as previously described.

[0064] **Figure 6A** illustrates a cross-sectional view of another exemplary catalytic pilot design, and **Figure 6B** illustrates a view along line A-A of **Figure 6A** with part of the structure removed for clarity. In this example, the catalytic pilot includes two catalyst stages, wherein the first catalyst stage includes two separate air intake regions, mixing regions, and catalyst structures. The combustor includes a catalytic pilot assembly 622 and a main swirler-injector assembly 624 interconnected with the combustor inlet region for receiving compressor discharge air. Referring to both **Figures 6A and 6B**, the pilot assembly 622 includes a first pilot inlet region 66 for intaking air, a first pilot fuel-air mixing region 62 located downstream of the first pilot inlet region 66, at least one first pilot fuel injector (not shown), a first catalyst 64, and a catalyst exit region 614. The pilot assembly 622 also includes a second pilot inlet region 67, a second pilot fuel-air mixing region 61 located downstream of the second pilot inlet region 67, at least one second pilot fuel injector (not shown), a second catalyst 63, and a catalyst exit region 614. Both the first and second catalysts 63 and 64 form a first stage of the catalytic pilot 622 upstream of the third catalyst 626 forming a second stage of the catalytic pilot 622. An inter-catalyst region 628 is located between the first and second pilot stages. The pilot assembly also includes a pilot outlet region 630 located downstream of the third catalyst 626.

[0065] The main swirler-injector assembly 624 includes a main swirler-injector assembly inlet region 632 for receiving air, a main swirler-injector assembly outlet region 634, a main swirler-injector assembly swirler 636 located downstream of the main swirler-injector assembly inlet region 632, at least one main swirler-injector assembly fuel injector located downstream of the swirler 636, a mixing region 637 located downstream of the fuel injector and upstream of the main swirler-injector assembly outlet region 634, and a main combustion or re-circulation zone 640 located downstream of the pilot assembly 622 exit region 630. As shown in **Figures 6A and 6B**, the combustor has a central axis L and the third catalyst 626 is located along the central axis. The main swirler-injector assembly inlet

region 632 and the main swirler-injector assembly swirler 636 are arranged in an annular configuration about the pilot assembly.

[0066] Compressed air enters the combustor and is received by the pilot assembly 622 and main swirler-injector assembly 624. The compressed air enters the pilot assembly 622 through the first and second pilot inlet regions 66 and 67. Pilot fuel from fuel line 651 is injected into the air flow by respective fuel injectors and mixed with the air in fuel-air mixing regions 61 and 62. Various active or passive mixing elements may be included in the fuel-air mixing regions. The fuel injectors are interconnected with fuel lines 651 via a fuel manifold or the like that may include valves or the like for modulating pilot fuel delivery. In this example, the pilot fuel is mixed with the pilot air in two distinct locations, both the fuel-air mixing regions 61 and 62, to generate a rich uniform fuel-air mixture to pass across two first stage catalysts 63 and 64. The higher temperature and leaner fuel-air mixture exiting the first stage catalysts 63 and 64 converge at an inter-catalyst region 628 where the gas velocity accelerates as the frontal cross-sectional area (i.e., viewed along the plane A-A) of the inter-catalyst region 628 reduces from the total frontal cross-sectional areas of the first and second pilot fuel-air mixing regions 61 and 62. In one variation, the frontal cross-sectional area of the inter-catalyst region 628 is exactly half the total frontal area of the first and second pilot fuel-air mixing regions 61 and 62 combined; however, other ratios are contemplated for various applications and designs. The leaner fuel-air mixture in the inter-catalyst region 628 passes across a third catalyst or second catalyst stage 626 that may be designed to perform with at least one of higher inlet temperature, higher velocity, and leaner fuel-air mixture than the first stage catalysts 63 and 64.

[0067] Compressed air also enters the main swirler-injector assembly 624 at main swirler-injector assembly inlet region 632. Fuel is injected by a main swirler-injector assembly fuel injector, which delivers fuel into the main swirler-injector assembly from a main swirler-injector assembly fuel manifold via a main fuel line 650 that may include a valve (not shown) or the like for modulating main swirler-injector assembly fuel delivery. The hot fuel and vitiated air mixture exiting the second stage catalyst 626 combusts entirely in the pilot outlet region 630 delivering hot vitiated air into the combustion zone 640 where it mixes with the main swirler-injector assembly air and fuel mixture that is delivered from the main swirler-injector assembly into the combustion zone.

[0068] In another variation, the pilot outlet region 630 is sufficiently small in length and/or volume so that spontaneous combustion of the fuel and vitiated air mixture does not occur within the pilot outlet region 630. Rather, combustion of the fuel and vitiated air mixture exiting second stage catalyst 626 occurs in the combustion zone 640 where the mixture mixes with the compressed air and fuel of the main swirler-injector assembly. The high temperature gases exiting the catalytic pilot mix with the LPM swirler-injector assembly gases in the re-circulation zone or combustion zone 640 to stabilize the LPM flame.

[0069] **Figure 7** illustrates a cross-sectional view of another exemplary variation of a catalytic pilot incorporated within an LPM combustor. In this example, compressor discharge air from a compressor enters the combustor and passes into the pilot assembly 722 and the main swirler-injector assembly 724. The compressed air enters the pilot assembly 722 through the pilot inlet region 702. Fuel is injected into the flow path by at least one first pilot fuel injector 701 where it mixes with air in the fuel-air mixing region 703. Active or passive mixing elements may be included in the fuel-air mixing region 703. The pilot fuel is mixed with the pilot air and generates a fuel-air mixture that passes across the pilot catalyst 704. The hot fuel-air mixture exiting the catalyst 704 mixes with fuel from at least one second pilot fuel injector 705 located downstream of the catalyst 704. The fuel injectors 701 and 705 may be interconnected with a fuel-manifold via fuel lines that may include valves for modulating pilot fuel delivery.

[0070] Compressed air also enters the main swirler-injector assembly 724 at the main swirler-injector assembly inlet region 718. Fuel is injected by the main swirler-injector assembly fuel injector 720, which may deliver fuel into the main swirler-injector assembly from a main swirler-injector assembly fuel manifold via a main fuel line that includes a valve or the like for modulating main swirler-injector assembly fuel delivery. The hot fuel and vitiated air mixture exiting the pilot assembly mixes with the main swirler-injector assembly air and fuel mixture that is delivered from the main swirler-injector assembly 724 into the combustion or re-circulation zone 707. As illustrated in this instance, catalyst 704 may be located along a central axis of the combustor with main swirler-injector assembly inlet region 718 and the main swirler-injector assembly fuel-air mixing region 721 arranged in an annular configuration about the pilot assembly 722.

[0071] In one exemplary operation, first pilot fuel injector 701 injects fuel, which mixes with the incoming pilot air in the pilot fuel-air mixing region 703. The pilot fuel is at least partially combusted on the catalyst 704 to generate a hot fuel-vitiated air mixture (or completely vitiated air mixture). The hot pilot fuel-vitiated air mixture is mixed with additional fuel through second pilot fuel injector 705 in the catalyst exit region 706 to vary the amount of fuel exiting the catalytic pilot. Second pilot fuel injector 705 may also serve as a diffusion flame to assist in the gas turbine start-up, i.e., an acceleration or loading sequence, until the compressor discharge temperature (CDT) is sufficiently high to sustain catalytic combustion. The hot fuel-vitiated air mixture mixes with the main swirler-injector assembly fuel and main swirler-injector assembly air that is preferably lean pre-mixed in the re-circulation region 707 where the balance of combustion takes place.

[0072] **Figure 8** illustrates a cross-sectional view of another exemplary catalytic pilot configuration. In this example, catalyst fuel injector 801 injects fuel, which mixes with the incoming pilot air 802 in the pilot-mixing region 803. The pilot fuel is combusted on the catalyst 804 to generate a hot fuel-vitiated air mixture. The pilot configuration is similar to that of **Figure 2 or 3**, except that the hot pilot fuel-vitiated air mixture passes through a swirler-type element 805 in the catalyst exit region to enhance the mixing of the pilot exit gas mixture with the LPM fuel-air within the re-circulation region 806 where the balance of combustion takes place. The swirler-type element 805 may be any suitable active or passive swirler, guide vane, baffle, or the like to enhance the mixing of the pilot exit gas mixture as it enters the re-circulation region 806. Swirler-type element 805 may enhance the mixing of the pilot assembly exit gases and main swirler-injector assembly gases to increase flame stability, reduce combustion dynamics within the re-circulation region 806, and minimize the volume needed in the re-circulation region 806 to achieve complete combustion.

[0073] **Figure 9** illustrates a cross-sectional view of another exemplary catalytic pilot configuration. This example is similar to **Figure 3** except that additional air is added at 92b, interconnected to the inter-stage region 98 located between catalyst 913a and catalyst 913b. Catalyst fuel injector 911 injects fuel, which mixes with the incoming first stage pilot air in the pilot-mixing region 92a. In this example, pilot air may enter in two regions 92a and 92b. In one example, less air enters regions 92a than in a configuration

without air inlet at region 92b (such as **Figure 3**). Reducing the amount of air entering region 92a results in a lower velocity and potentially richer fuel-to-air ratio entering the first stage catalyst 913a.

[0074] The pilot fuel and air is combusted on the first stage catalyst 913a to generate a hot fuel-vitiated air mixture. The hot pilot fuel-vitiated air mixture is diluted and mixed with additional air entering at 92b upstream of the second stage catalyst 913b and before further combustion of the pilot fuel. After passing second stage catalyst 913b, the hot fuel-vitiated air mixture exiting the second stage catalyst may spontaneously combust within the catalyst exit region 914, or exit region 914 may be sufficiently small such that spontaneous combustion does not occur. The high temperature gases exiting the catalytic pilot mix with the LPM swirler-injector assembly gases in the re-circulation zone 919 to stabilize the LPM flame as previously described.

[0075] The exemplary catalytic pilot configurations shown in **Figures 2-9** are illustrated with the catalytic pilot generally disposed on the center axis of the LPM swirler-injector assembly. The catalytic pilot, however, may be placed off-axis from the LPM swirler-injector assembly with the hot gas exiting the catalytic pilot into the combustion or re-circulation zone of the LPM swirler-injector assembly. The catalytic pilot may also include one or more annular catalysts incorporated into the main swirler-injector assembly with the hot gas exiting the catalytic pilot into the re-circulation zone of the main swirler-injector assembly.

[0076] **Figure 10** illustrates a cross-sectional view of an exemplary off-axis catalytic pilot configuration. In this example, one or more catalytic pilots 1000 are disposed around a central main swirler-injector assembly 1010. The catalytic pilot 1000 includes a catalyst fuel injector 1002, fuel-air mixing region 1001, catalyst 1003, and catalyst exit region 1004. The main swirler-injector assembly 1010 includes fuel injector 1005 and a fuel-air-mixing element 1006 such as a typical swirler or the like.

[0077] Catalytic pilots 1000 and main swirler-injector assembly 1010 receive compressor discharge air at locations 1007 and 1008 respectively. The air is mixed with the pilot fuel 1002 and main fuel 1005 in mixing regions 1001 and 1008 respectively. The catalytic pilot fuel 1002 is at least partially combusted by catalyst 1003 to generate hot

vitiated gases exiting the catalytic pilot 1000. The hot vitiated gases mix with the LPM fuel-air mixture in the re-circulation region 1009 where the balance of combustion takes place. The volume of catalyst exit region 1004 may be varied (including a minimal volume) depending on the particular application to achieve the desired exit conditions of catalytic pilot 1000.

[0078] Additionally, the catalytic pilot configuration of **Figure 10** may include multiple stages of catalyst 1003 similar to those described with regard to **Figures 3, 5, 6, and 9**. For example, each catalytic pilot 1000 may include a first and second catalyst stage located serially in the flow path through one or more catalytic pilots 1000, second pilot fuel injectors, exit swirlers, and the like.

[0079] **Figure 11** illustrates a cross-sectional view of an annular catalytic pilot configuration. In this example, an annular catalytic pilot 1102 is illustrated disposed around a central burner 1101, which may be either a diffusion flame or LPM burner, and has an annular LPM swirler-injector assembly 1103 positioned around the catalytic pilot 1102. The catalytic pilot generally includes the catalyst fuel injector 1104, fuel-air mixing region 1105, catalyst 1106, and catalyst exit region 1107. In this configuration the hot vitiated gases exiting the catalytic pilot 1102 mix with the fuel-air mixture exiting the LPM swirler-injector assembly 1103 to complete the combustion process and stabilize the flame in the re-circulation zone 1108. The central burner 1101 may be a diffusion flame burner to stabilize combustion downstream of the LPM swirler-injector assembly 1103 during an acceleration or engine loading sequence. Additionally, a first and second stage catalyst may be included in the annular catalytic pilot configuration, and exit region 1107 may be varied in volume (including minimal volume) to achieve desired exit conditions of the catalytic pilot 1102.

[0080] As will be recognized by those skilled in the art various other designs and configurations are possible to stabilize an LPM flame with the output of a catalytic pilot assembly. For example, various configurations of catalytic assemblies, multiple catalyst stages, exit region volumes, mixing elements, and the like may be combined depending on the particular application and desired catalytic pilot exit conditions.

[0081] **Control and Operating Strategies**

[0082] According to another aspect of the present invention various methods and strategies for controlling and operating the catalytic pilot are provided. Exemplary control and operating methods include methods for achieving catalyst light-off, preferred catalyst conversion rates, preferred catalyst exit temperatures, and maintaining preferred catalyst performance over desired operating ranges and life of the catalyst within the catalytic pilot.

[0083] A. Acceleration and Engine Loading

[0084] A gas turbine engine system desirably operates in a manner such that the catalyst will sustain catalytic combustion when fuel to the catalyst is initiated. One exemplary method includes monitoring the compressor discharge temperature (CDT) and/or catalyst inlet temperature during an acceleration and engine loading sequence until it is above the catalyst LOT. When the CDT is equal to or above the catalyst LOT, fuel may then be delivered to the catalyst. This method is desirable when the LPM burner is capable of performing the acceleration and loading sequence without the added stability of a pilot flame. In applications where the LPM burner performance is improved with assistance from a pilot flame for stability during an acceleration and loading sequence, various methods described below may be used.

[0085] In one exemplary method for operating a combustor with a catalytic pilot includes using a diffusion pilot to stabilize the LPM flame during the acceleration and loading sequence. When the compressor discharge air temperature is high enough to support catalytic combustion in the catalytic pilot and thereby stabilize the LPM flame, a transition is made from the diffusion burner to the catalytic pilot. This exemplary method is illustrated in **Figure 12** where various parameters of a gas turbine engine system are plotted with respect to time. While the turbine accelerates to full speed and loads to full load, the diffusion pilot is fueled to assist and stabilize the LPM burner. During the acceleration and loading sequence the CDT increases to a level above the catalyst light-off temperature. At a time when the CDT is greater than the catalyst light-off temperature, the diffusion pilot fuel may be decreased while the catalytic pilot fuel is increased. The transition from fueling the diffusion pilot to fueling the catalytic pilot may occur over a range of load and time near or after the CDT temperature rises above the catalyst LOT. At the end of the transition period, the diffusion pilot fuel flow may be reduced to zero and the LPM burner remains stabilized by the catalytic pilot operation. Depending on the

particular system and application, the transition period may vary in time and in relation to the speed and/or load of the turbine. For example, the diffusion pilot fuel could begin to decrease before the CDT is above the catalyst LOT. The CDT may be measured at the compressor discharge air inlet of the combustor, the inlet for the catalytic pilot, or anywhere in between. CDT may also be estimated from turbine operating conditions.

[0086] In another exemplary method a duct burner or the like may be used to increase the inlet air temperature such that the CDT (or catalytic pilot intake temperature) is sufficiently high to light-off the catalyst and stabilize the LPM burner throughout the acceleration and loading sequence. This approach is illustrated in **Figure 13** with the temperature profile is graphed through several components of the gas turbine system. In a typical gas turbine system without a duct burner, as shown in 13a, the air is drawn through a duct 1301 into the compressor 1302. The compressor compresses the air to a higher pressure and temperature 1303. The resulting compressor discharge temperature typically remains below the catalyst light-off temperature 1304. The compressed air is further heated in the combustor 1305 to generate hot vitiated air. The hot vitiated air passes through the turbine section 1306, extracting energy and cooling the vitiated air. The cooled vitiated air exits the system through the exhaust stack 1307.

[0087] In a gas turbine system with a duct burner, as shown in 13b, the air is drawn through a duct 1308 containing a duct heater or burner 1309. The duct burner 1309 heats the intake air to a higher temperature 1310. Duct burner 1309 may be any suitable burner or heater capable of increasing the temperature of the intake air. The preheated air is compressed through the compressor 1311 to a higher pressure and temperature 1312. The resulting compressor discharge air temperature is now greater than the light-off temperature of the catalyst so the catalytic pilot can now be used to stabilize the LPM burner. The balance of the gas turbine system operates similar to 13a.

[0088] In another exemplary method an electrical heater may be used upstream of the catalytic pilot to pre-heat air entering the catalyst to a temperature where the catalyst may light-off and stabilize the combustion downstream of the LPM swirler-injector assembly. This approach is schematically illustrated in **Figure 14**. A temperature profile is graphed through several components of a gas turbine system both for a system with and without an electrical pre-heater. In 14a, an exemplary catalytic pilot assembly without a

pre-heater is illustrated. The air temperature 1401 entering the catalytic pilot is below the catalyst light-off temperature 1402 and the catalyst cannot support catalytic combustion of the air and the pilot fuel. Therefore, the gas temperature exiting the pilot 1403 is unchanged and the catalytic pilot does not stabilize the combustion downstream of the LPM swirler-injector assembly. In 14b, an electrical heating element 1404 is disposed upstream of an exemplary catalytic pilot, or at least upstream of the catalyst, to heat the inlet pilot air to a temperature 1405 above the catalyst light-off temperature 1402. The catalytic pilot is now active and the pilot exit temperature 1406 is high enough to stabilize combustion downstream of the LPM swirler-injector assembly.

[0089] In another exemplary method, a pre-burner, such as an annular pre-burner located around the main LPM swirler-injector assembly or the like may be used to provide a sufficient increase in temperature to the incoming combustor air to support both catalyst light-off within the catalytic pilot and help stabilize combustion downstream of the main LPM swirler-injector assembly. The pre-burner could operate during start-up and acceleration sequences as well as at full-load. Various configurations of a pre-burner in a catalytic pilot combustion system will be apparent to those skilled in the art.

[0090] In another exemplary method, the pilot fuel may be doped with hydrogen during a start-up or acceleration sequence so as to initiate catalyst light-off at very low temperatures, e.g., near ambient temperature. A fuel processor as part of the fuel skid (not shown) or the like may generate the hydrogen. Alternatively, the hydrogen may be a provided by a local source such as a high-pressure cylinder or as a process gas from an adjacent chemical plant.

[0091] B. Catalytic Pilot Operation Methods

[0092] In another aspect of the invention, various methods are provided for operating the catalytic pilot system in a manner to maintain preferred catalyst exit conditions, such as catalyst conversion (i.e., the ratio of fuel combusted by catalyst) and exit temperature, that stabilize the LPM flame over the life of the catalyst.

[0093] In one exemplary operating method the catalytic pilot adiabatic combustion temperature is controlled. The pilot fuel flow may be based on a schedule of catalyst adiabatic combustion temperature (Tad demand) versus load or some other system

characteristic consistent with load, such as compressor discharge temperature, exhaust gas temperature, turbine inlet temperature, total fuel flow to the engine, or the like. The control system may determine the pilot airflow based upon engine measurements of compressor discharge pressure, compressor discharge temperature, inlet bell mouth pressure, ambient temperature, inlet guide vane position, or the like. The control system may then use the pilot airflow, pilot inlet temperature, and fuel temperature to calculate the pilot fuel flow to attain the Tad demand. This approach is desirable in systems where the loss in catalyst activity resulting from catalyst aging, poisoning, or the like is negligible.

[0094] In another exemplary method for operating the catalytic pilot system which includes compensating for changes in catalyst activity over time uses closed loop feedback control on combustion dynamics of the main combustion chamber (i.e., the re-circulation or combustion zone). Combustion dynamics may include, for example, the dynamic pressure measured by the root-mean-squared (RMS) value of pressure variations within the main combustor chamber. Higher RMS values are generally indicative of combustion instability. In the event catalyst activity changes due to catalyst aging, poisoning, or the like, the pilot fuel flow may be adjusted based on one or more measured combustion dynamics within the combustor. As catalyst activity decreases, the catalyst exit temperature may fall below the preferred temperature range that stabilizes the LPM flame, which may increase the measured combustion dynamics. To compensate, the control system may increase the pilot fuel flow to increase the catalyst exit temperature, which may stabilize the LPM flame and reduce combustion dynamics to a desirable level. A desirable level of combustion dynamics generally depends on the specific gas turbine and combustor design. For illustrative purposes, in a system where less than approximately 1 psi root-mean-squared value is a desirable combustion dynamic level the catalytic pilot fuel flow may be increased to increase the catalyst exit temperature and reduce the combustion dynamics below the desired level of 1 psi RMS. As will be recognized by those skilled in the art, however, there is a limit on how much the pilot fuel flow may be increased for a particular system. The upper limit is generally determined, at least in part, on the particular system and the particular application.

[0095] Another exemplary method for operating the catalytic pilot system includes closed loop feedback control on the catalyst exit temperature. In this example, the pilot

fuel flow is based on a schedule of catalyst exit temperature versus load or an engine fundamental characteristic consistent with load, such as compressor discharge temperature, exhaust gas temperature, turbine inlet temperature, total fuel flow to the engine, or the like. This method may accommodate for changes in catalyst activity resulting from catalyst aging, poisoning, or the like. Closed loop feedback control on the catalyst exit temperature may also be used in conjunction with other control strategies to accommodate for varying catalyst activity, for example, to supplement an operating strategy that does not compensate for catalyst aging.

[0096] Another exemplary method for operating the catalytic pilot system includes a fixed percentage fuel split schedule between the catalytic pilot and the main burner for a given load on the engine as shown below in Table 1. The split of fuel between the catalytic pilot and LPM may be based on schedules of fuel split versus load or another engine fundamental consistent with load, such as compressor discharge temperature, exhaust gas temperature, turbine inlet temperature, total fuel flow to the engine, or the like. This method generally does not accommodate for the loss in catalyst activity resulting from catalyst aging or poisoning. Therefore, it is desirable, but not necessary, that some level of closed loop feedback control, such as catalyst exit temperature or combustion dynamics in the main chamber also be included to supplement the fixed fuel schedule.

[0097] Table 1: Example of fixed percentage fuel split schedule to control a catalytic pilot system.

	Fuel Split	
% Load	**% Pilot**	**% Main**
100	25%	75%
90	24%	76%
80	23%	77%
70	22%	78%
60	21%	79%
50	20%	80%
40	19%	81%
30	18%	82%
20	17%	83%
10	16%	84%
FSNL	15%	85%

[0098] Table 1 is illustrative only and various other fixed fuel schedules will be apparent to those skilled in the art.

[0099] Another exemplary method for operating the catalytic pilot system includes a fixed mass flow fuel schedule is shown below in Table 2. The fuel flow to the catalytic pilot can be based on a schedule of fixed fuel flow versus load or some engine fundamental consistent with load, such at compressor discharge temperature, exhaust gas temperature, turbine inlet temperature, total fuel flow to the engine, or the like. This method generally does not accommodate for the loss in catalyst activity resulting from catalyst aging or poisoning. Therefore, it is desirable, but not necessary, that some level of closed loop feedback control, such as catalyst exit temperature or combustion dynamics in the main chamber also be included to supplement the fixed mass flow fuel schedule.

[00100] Table 2: Example of fixed mass fuel flow schedule to control a catalytic pilot system.

% Load	Fuel Flow **Pilot (pph)**
100	100
90	99
80	98
70	97
60	96
50	95
40	94
30	93
20	92
10	91
FSNL	90

[00101] Table 2 is illustrative only and various other fixed fuel schedules will be apparent to those skilled in the art.

[00102] In another exemplary system and method of operation, the catalytic pilot is configured to operate at high equivalence ratios and increased catalyst exit gas temperatures. For example, when LPM flame stability is improved by supplementing the main flame with hot vitiated air from a diffusion pilot flame, the resulting NO_x may be typical of the profile shown in **Figure 15.** The NO_x generally increases with the added fuel (heat/temperature) from the diffusion pilot. In general, additional stability is attained from the diffusion pilot, but at the cost of additional NO_x emissions generated by the higher temperature combustion of the diffusion flame pilot.

[00103] In contrast, when LPM flame stability is improved by supplementing the main flame with hot vitiated air from a catalytic pilot, the resulting NO_x may decrease as additional fuel is delivered to the catalytic pilot as illustrated in **Figure 15**. The additional fuel adds heat and increases the temperature of the gas exiting from the catalytic pilot to stabilize the main LPM flame without additional NO_x emissions. It should be understood that the graph of resulting NO_x for a diffusion flame pilot and a catalytic pilot for given pilot fuel fraction percentages is illustrative only and that the curves may vary in shape and value depending on the particular system such as pilot and combustor designs as well as fuel, pressure, and the like. For example, the catalytic pilot emission curve may remain nearly constant or slightly increase with the added fuel (heat/temperature) from the catalytic pilot as illustrated in **Figure 16**, but generally will be less than a similar system with a diffusion flame pilot.

[00104] Further, the stability of the LPM flame may be measured in terms of lean-blow-out (LBO) and dynamic pressure. A plot of catalyst exit temperature ranging from approximately 1200 to 1800 °F versus pilot equivalence ratio (Φ) is shown in **Figure 17** and illustrates for that for an exemplary catalyst design the directly proportional relationship between exit temperature and Φ. Table 3 below summarizes the improved LBO performance with increasing Φ (equivalent to catalyst exit gas temperature).

[00105] Table 3: Lean blow-out (LBO) performance for different pilot configurations.

Pilot Configuration	Φ_{pilot}	Φ_{LBO}
Premixed	0.08	0.51
	0.24	0.51
	0.48	0.50
Catalytic	0.08	0.52
	0.24	0.50
	0.48	0.46
Diffusion	0.08	0.49
	0.24	0.46
	0.48	0.45

[00106] Dynamic pressure may be measured by the root mean square (RMS) of the combustor pressure fluctuations. Higher RMS values generally indicate combustion instability. **Figure 18** illustrates an exemplary plot of the RMS pressure versus the overall equivalence ratio for three different pilot configurations at several different pilot Φ. In particular, a diffusion pilot, premixed pilot, and a catalytic pilot configuration are compared. The exemplary plot shows that the most stable system (lowest RMS) was measured with a catalytic pilot operating at its highest Φ (equivalent to outlet gas temperature). Therefore, improved combustor stability may be improved by both the catalytic pilot operating at a high equivalence ratio and increased catalyst exit gas temperature.

[00107] When a catalytic piloted combustor is in operation, the over-all fuel-air ratio or air fuel ratio (AFR), equal to the pilot fuel plus main fuel divided by total combustor air, determines the final combustor exit temperature. If one changes the pilot fuel, a corresponding change generally must be made to the main fuel to maintain the same combustor exit temperature. For example, if the pilot fuel flow is increased by 10pph, then the main fuel flow should be decreased by 10pph so that the over-all fuel-air ratio and combustor exit temperature remains unchanged.

[00108] With a catalytic pilot, the relationship between catalyst exit temperature and pilot fuel-air ratio is generally dependent on the catalyst design. **Figure 19** illustrates the difference where catalyst A and B may yield the same exit temperature but with different

fuel-air ratios. For example, for the same exit temperature, the fuel air ratio for catalyst A is lower than catalyst B.

[00109] In two exemplary systems with a catalytic pilot, one with catalyst A and the other with catalyst B, the inlet fuel-air ratio will differ (as illustrated in **Figure 19**) to produce the same exit temperature. As a result, the composition of the pilot exit gas of catalyst A will differ from that of catalyst B. For example, assume catalyst A has approximately a 25% conversion rate versus catalyst B with approximately a 50% conversion rate. In order to attain the same catalyst exit temperatures, the fuel concentration or mass fuel flow to catalyst A will be twice that of catalyst B. The exit composition of catalyst A will contain, for example, 75pph fuel versus 25pph exiting catalyst B according to the following exemplary conditions:

Catalyst A
Tin = 450 °C with 100pph fuel
x25% conversion of fuel
Tout = 900 °C with 75pph unburned fuel

Catalyst B
Tin = 450 °C with 50pph fuel
x50% conversion of fuel
Tout = 900 °C with 25pph unburned fuel

[00110] The unburned fuel exiting the pilot will combust without forming NO_x (or possibly forming very little NO_x) because of the uniform and lean fuel-air mixture. To maintain the same over-all fuel-air ratio and combustor exit temperature of piloted combustor with catalyst A and piloted combustor with catalyst B, the main fuel flow of combustor A will be 50pph less than the main fuel flow of combustor B. Therefore, the available fuel to generate NO_x in the main LPM flame will be less in combustor A relative to combustor B and therefore combustor A may have a lower NO_x emissions than combustor B even though the pilot exit gas temperature for both combustors may be the same. Furthermore, the total mass flow exiting pilot catalyst A will be greater than pilot catalyst B. The additional high temperature mass flow exiting the catalytic pilot to the LPM flame may provide additional flame stability. The amount of stability gained may depend on the design and operation of the main LPM combustor.

[00111] For an exemplary combustor exit temperature, corresponding generally to the AFR as described above, there is generally a maximum pilot-to-main fuel ratio where the main burner may become too lean to sustain combustion, resulting in lean-blow-out (LBO). In one exemplary combustion system with a combustor exit temperature corresponding to an AFR of approximately 56, the highest pilot-to-main fuel ratio attainable is in the range of approximately 0.14 to 0.16. It may be possible, however, to attain pilot-to-main fuel ratios greater than 0.16 for higher combustor exit temperatures or AFR.

[00112] The above detailed description is provided to illustrate exemplary embodiments and is not intended to be limiting. It will be apparent to those skilled in the art that numerous modification and variations within the scope of the present invention are possible. For example, different aspects of catalytic pilot configurations including various mixers, multiple catalyst stages, inlet/exit regions, fuel injectors, and the like may be interchanged depending on the particular application. Additionally, it will be apparent to those skilled in the art that the numerous modification and variations within the scope of the present invention may be applied to gas engine turbines, burner, boilers, furnaces, and the like with similar benefits as described. Further, numerous other materials and processes not explicitly described herein may be used within the scope of the exemplary methods and structures described as will be recognized by those skilled in the art. Accordingly, the present invention is defined by the appended claims and should not be limited by the description herein.

CLAIMS

1. A combustor for a combustion system, comprising:

a combustor inlet region for receiving air;

at least one pilot assembly housing interconnected with the combustor inlet region; the pilot assembly including:

a pilot inlet region for receiving at least a portion of the air;

a first catalyst located downstream of the pilot inlet region; and

a pilot fuel injector for delivering pilot fuel upstream of the first catalyst; and

a pilot outlet region located downstream of the first catalyst;

at least one main swirler-injector assembly interconnected with the combustor inlet region; the swirler-injector assembly including:

a main swirler-injector assembly inlet region for receiving at least a portion of the air;

a main swirler-injector assembly fuel injector located downstream of the main swirler-injector assembly inlet region; and

a combustion zone located downstream of the main swirler-injector assembly fuel injector and downstream of the pilot assembly.

2. The combustor of claim 1, wherein the at least one pilot assembly further includes a second catalyst located downstream of the first catalyst.

3. The combustor of claim 2, wherein the second catalyst is configured to perform with a leaner fuel-air mixture than the first catalyst.

4. The combustor of claim 2, wherein the second catalyst is configured to perform with a higher inlet temperature than the first catalyst.

5. The combustor of claim 2, wherein an inter-catalyst region is located between the first catalyst and the second catalyst, and the pilot inlet region includes a cross-sectional area that is larger than the cross-sectional area of the inter-catalyst region.

6. The combustor of claim 5, wherein the second catalyst is configured to perform with a higher velocity fuel-air mixture than the first catalyst.

7. The combustor of claim 5, wherein the inter-catalyst region includes a second air inlet for receiving air upstream of the second catalyst.

8. The combustor of claim 5, wherein the combustor is configured such that fuel and air delivered to the pilot assembly results in a hot fuel and vitiated-air mixture exiting the second catalyst and combusting within the pilot outlet region such that hot vitiated air is delivered to the main swirler-injector assembly combustion zone where it mixes with fuel and air that is delivered from the main swirler-injector assembly.

9. The combustor of claim 5, wherein the combustor is configured such that fuel and air delivered to the pilot assembly results in a hot fuel and vitiated-air mixture exiting the second catalyst, mixing with fuel and air that is delivered from the main swirler-injector assembly and combusting within the combustion zone.

10. The combustor of claim 1, wherein the pilot inlet region includes a cross-sectional area that increases with distance towards the first catalyst.

11. The combustor of claim 1, wherein the at least one pilot assembly further includes a pilot fuel-air mixing region located downstream of the pilot inlet region wherein the pilot fuel injector delivers pilot fuel into the pilot fuel-air mixing region.

12. The combustor of claim 1, wherein the pilot fuel injector delivers fuel from a pilot fuel manifold via a pilot fuel line that includes a valve for modulating pilot fuel delivery.

13. The combustor of claim 1, wherein the main fuel injector delivers fuel from a main fuel manifold via a main fuel line that includes a valve for modulating main fuel delivery.

14. The combustor of claim 1, wherein the at least one pilot assembly further includes a second pilot fuel injector located downstream of the first catalyst.

15. The combustor of claim 14, wherein the second pilot fuel injector serves as a diffusion flame.

16. The combustor of claim 1, wherein the first catalyst generates a mixture of fuel and vitiated air that combusts within the pilot outlet region such that vitiated air is delivered to the combustion zone.

17. The combustor of claim 1, wherein the first catalyst generates a mixture of fuel and vitiated air that exits the pilot outlet region such that the mixture of fuel and vitiated air is delivered to the combustion zone.

18. The combustor of claim 1, wherein the at least one pilot further includes a mixer element located downstream of the first catalyst.

19. The combustor of claim 1, wherein the combustor further includes a heater to increase the temperature of the air upstream of the first catalyst.

20. The combustor of claim 1, wherein the combustor is interconnected to an air duct including a heater to increase the temperature of compressor discharge air upstream of the pilot inlet region.

21. The combustor of claim 1, wherein the pilot inlet region includes a heater to increase the temperature of compressor discharge air upstream of the first catalyst.

22. The combustor of claim 1, wherein the pilot inlet region and the first catalyst is annular in shape.

23. The combustor of claim 1, wherein the combustor includes a central axis and the pilot assembly is located along the central axis; the main swirler-injector assembly inlet region and the main swirler-injector assembly fuel-air mixing region are annular in shape about the pilot assembly.

24. The combustor of claim 1, wherein the combustor includes a central axis and the main swirler-injector assembly is located along the central axis; and the pilot assembly is annular in shape about the main swirler-injector assembly fuel-air mixing region.

25. The combustor of claim 1, wherein the pilot fuel is doped with hydrogen to achieve catalyst light-off.

26. The combustor of claim 1, further including a fuel processor integral to the fuel skid, wherein the pilot fuel is doped with hydrogen from the fuel processor to achieve catalyst light-off.

27. The combustor of claim 1, further including a preburner disposed upstream of the pilot assembly.

28. A combustor for a combustion system, comprising:

a combustor inlet region for receiving compressed air;

at least one pilot assembly interconnected with the combustor inlet region; the pilot assembly comprising:

a first pilot inlet region for receiving compressed air;

a first pilot fuel-air mixing region located downstream of the first pilot inlet region;

a first pilot fuel injector for delivering pilot fuel into the first pilot fuel-air mixing region;

a first catalyst located downstream of the first fuel-air mixing region;

a first catalyst exit region located downstream of the first catalyst;

a second pilot inlet region for receiving compressed air;

a second pilot fuel-air mixing region located downstream of the second pilot inlet region;

a second pilot fuel injector for delivering pilot fuel into the second pilot fuel-air mixing region;

a second catalyst located downstream of the second fuel-air mixing region;

a second catalyst exit region located downstream of the second catalyst;

a third catalyst located downstream of the first and second catalyst;

an inter-catalyst region located between the first and second catalyst, and the third catalyst and downstream of the first catalyst exit region and the second catalyst exit region, wherein the first catalyst exit region and the second catalyst exit region converge into the inter catalyst region; and

a pilot outlet region located downstream of the third catalyst;

at least one main swirler-injector assembly interconnected with the combustor inlet region; the swirler-injector assembly comprising

a main swirler-injector assembly inlet region for receiving compressed air;

a main swirler-injector assembly fuel-air mixing region located downstream of the main swirler-injector assembly inlet region; and

a main swirler-injector assembly fuel injector for delivering fuel into the main swirler-injector assembly fuel-air mixing region;

a combustion zone located downstream of the pilot assembly.

29. The combustor of claim 28, wherein the first pilot inlet region has a cross-sectional area and the second pilot inlet region has a cross-sectional area, and the combined cross-sectional areas of the first and second pilot inlet regions is larger than the cross-sectional area of the inter-catalyst region.

30. The combustor of claim 28, wherein the third catalyst is configured to perform with at least one of a higher inlet temperature, higher velocity, and leaner fuel-air mixture than at least one of the first and second catalyst.

31. The combustor of claim 28, wherein the combustor includes a central axis and the third catalyst is located along the central axis; the main swirler-injector assembly inlet region and the main swirler-injector assembly fuel-air mixing region are annular in shape about the pilot assembly.

32. The combustor of claim 28, wherein the first pilot fuel-air mixing region and the second pilot fuel-air mixing region include a mixer.

33. The combustor of claim 28, wherein the combustor is configured such that fuel and air delivered to the pilot assembly results in a hot fuel and vitiated-air mixture exiting the third catalyst and combusting within the pilot outlet region such that hot vitiated air is delivered to the main swirler-injector assembly combustion zone where it mixes with fuel and air that is delivered to the main swirler-injector assembly.

34. The combustor of claim 28, wherein the combustor is configured such that fuel and air delivered to the pilot assembly results in a hot fuel and vitiated-air mixture exiting the third catalyst, mixing with fuel and air that is delivered to the main swirler-injector assembly and combusting within the combustion zone.

35. A combustor for a combustion system, comprising:

a combustor inlet region;

at least one pilot assembly interconnected with the combustor inlet region; the pilot assembly comprising:

a pilot inlet region for receiving compressed air;

a pilot fuel-air mixing region located downstream of the pilot inlet region;

a first pilot fuel injector for delivering pilot fuel into the pilot fuel-air mixing region;

at least one catalyst located downstream of the fuel-air mixing region;

a pilot outlet region located downstream of the catalyst; and

a second pilot fuel injector located downstream of the catalyst in the pilot outlet region;

at least one main swirler-injector assembly interconnected with the combustor inlet region; the main swirler-injector assembly comprising

a main swirler-injector assembly inlet region;

a main swirler-injector assembly outlet region;

a main swirler-injector assembly fuel-air mixing region located downstream of the main swirler-injector assembly inlet region; and

a main swirler-injector assembly fuel injector for delivering fuel into the main swirler-injector assembly fuel-air mixing region; and

a combustion zone located downstream of the pilot assembly.

36. The combustor of claim 35, wherein the combustor is configured such that fuel and air delivered to the first pilot fuel injector results in a hot fuel and vitiated-air mixture exiting the catalyst, mixing with fuel delivered to the second pilot fuel injector, mixing with fuel and air from the main swirler-injector assembly and combusting within the combustion zone.

37. The combustor of claim 35, wherein the combustor is configured such that fuel and air is delivered to the second pilot fuel injector prior to catalyst light off to support combustion of fuel and air from the main swirler-injector assembly in the combustion zone.

38. The combustor of claim 35, wherein the at least one pilot assembly further includes a second catalyst located downstream of a first catalyst.

39. The combustor of claim 38, wherein the second catalyst is configured to perform with at least one of a leaner fuel-air mixture, higher inlet temperature, and higher velocity than the first catalyst.

40. A method of operating a combustion system including a catalytic pilot assembly and a main swirler-injector assembly, comprising:
receiving compressor discharge air through an inlet of the catalytic pilot assembly and an inlet of the main swirler-injector assembly;
delivering fuel to the main swirler-injector assembly;

monitoring the compressor discharge air temperature at a location upstream of a catalyst that is located within the catalytic pilot assembly; and

delivering fuel to the catalytic pilot assembly upstream of the catalyst when the monitored temperature of the compressor discharge air is sufficiently high to sustain catalytic combustion.

41. The method of claim 40, further including heating the compressor discharge air upstream of a catalyst within the catalytic assembly if the compressor discharge air temperature is below a temperature to sustain catalytic combustion.

42. The method of claim 41, wherein the temperature of the compressor discharge air is increased in a duct interconnected with the combustor.

43. The method of claim 42, wherein the temperature of the compressor discharge air is increased by a duct burner.

44. The method of claim 41, wherein the temperature of the compressor discharge air is increased upstream of the catalyst and within the catalytic pilot assembly.

45. The method of claim 44, wherein the temperature of the compressor discharge air is increased by an electrical heater disposed in the inlet of the pilot assembly.

46. The method of claim 40, further including delivering fuel to a diffusion pilot burner disposed within the combustor until the temperature of the compressor discharge air temperature entering the catalytic pilot assembly is sufficiently high to sustain catalytic combustion.

47. The method of claim 46, further including reducing fuel delivered to the diffusion pilot burner and increasing fuel delivered to the catalytic pilot

assembly when the compressor discharge temperature reaches the temperature to sustain catalytic combustion.

48. The method of claim 40, wherein the fuel delivered to the catalytic pilot assembly is doped with hydrogen.

49. A method for operating a combustion system piloted by a catalytic pilot, comprising:

passing pilot fuel and air through the catalytic pilot including a catalyst, wherein a catalytic pilot exit region is disposed upstream of a main swirler-injector assembly combustion zone; and

adjusting at least one of the fuel and the air delivered to the catalytic pilot to vary catalyst exit conditions.

50. The method of claim 49, wherein the catalytic exit conditions are varied to support combustion in the main swirler-injector assembly combustion zone.

51. The method of claim 49, wherein the catalytic exit conditions include a catalytic pilot exit temperature and the pilot fuel is adjusted to vary the catalytic pilot exit temperature.

52. The method of claim 51, wherein the catalytic pilot has a pilot fuel conversion rate for combusting pilot fuel of less than 50% such that the catalytic exit conditions include 50% of the pilot fuel uncombusted.

53. The method of claim 51, wherein the catalytic pilot has a pilot fuel conversion rate for combusting pilot fuel is approximately 25% such that the catalytic exit conditions include approximately 75% of the pilot fuel uncombusted.

54. The method of claim 49, wherein the catalytic exit conditions include a catalytic pilot exit temperature and a pilot fuel conversion rate, and at least

one of the pilot fuel exit temperature and pilot fuel conversion rate are adjusted to reduce NO_x emissions.

55. The method of claim 49, further including determining an adiabatic combustion temperature at the catalyst inlet, and adjusting the pilot fuel to maintain the adiabatic combustion temperature at the catalyst inlet within a predetermined range.

56. The method of claim 55, wherein the adiabatic temperature is determined by determining the air and fuel flows through the pilot, the catalyst inlet temperature, and the fuel temperature.

57. The method of claim 55, wherein the pilot fuel is adjusted based on a schedule of adiabatic combustion temperature versus a system characteristic associated with load.

58. The method of claim 57, wherein the system characteristic associated with load includes at least one of engine load, compressor discharge temperature, exhaust gas temperature, turbine inlet temperature, and total engine fuel flow.

59. The method of claim 49, further including determining an adiabatic combustion temperature at the catalyst outlet, and adjusting the pilot fuel to maintain the adiabatic combustion temperature at the catalyst inlet within a predetermined range.

60. The method of claim 59, wherein the adiabatic temperature is determined by determining the air and fuel flows through the pilot, the catalyst inlet temperature, and the fuel temperature.

61. The method of claim 59, wherein the pilot fuel is adjusted based on a schedule of adiabatic combustion temperature versus a system characteristic associated with load.

62. The method of claim 61, wherein the system characteristic associated with load includes at least one of engine load, compressor discharge temperature, exhaust gas temperature, turbine inlet temperature, and total engine fuel flow.

63. The method of claim 49, wherein the pilot fuel is adjusted based on a fixed percentage fuel split schedule between the catalytic pilot and the main swirler-injector assembly for a given system characteristic associated with load.

64. The method of claim 63, wherein the system characteristic associated with load includes at least one of engine load, compressor discharge temperature, exhaust gas temperature, turbine inlet temperature, and total engine fuel flow.

65. The method of claim 49, wherein the pilot fuel is adjusted based on closed loop feedback control on combustion dynamics of the main swirler-injector assembly combustion zone.

66. The method of claim 65, wherein if the combustion dynamics exceed a threshold value, the pilot fuel is increased.

67. The method of claim 65, wherein the combustion dynamics of the main swirler-injector assembly combustion zone include a measure of the root-mean-squared value of pressure variations within the main swirler-injector assembly combustion zone.

68. The method of claim 49, wherein the pilot fuel is adjusted based on closed loop feedback control on catalyst exit temperature.

69. The method of claim 68, wherein the pilot fuel is adjusted based on a schedule of the catalyst exit temperature versus a system characteristic associated with load.

70. The method of claim 69, wherein the system characteristic associated with load includes at least one of engine load, compressor discharge temperature, exhaust gas temperature, turbine inlet temperature, and total engine fuel flow.

71. The method of claim 49, wherein the pilot fuel is adjusted based on a fixed mass fuel schedule for a given system characteristic associated with load.

72. The method of claim 71, wherein the system characteristic associated with load includes at least one of engine load, compressor discharge temperature, exhaust gas temperature, turbine inlet temperature, and total engine fuel flow.

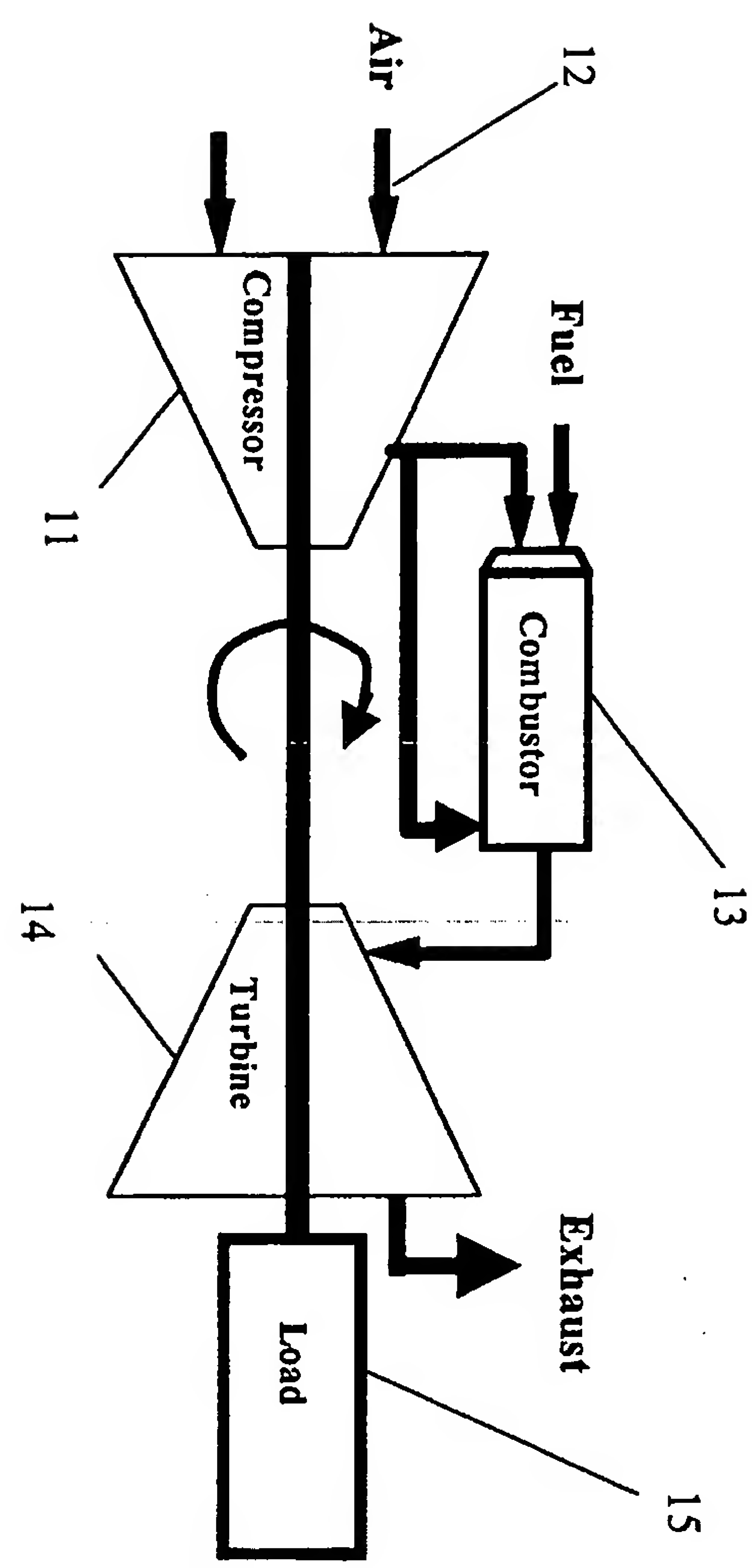

Air
12
Fuel
Compressor
11
Combustor
13
14
Turbine
Exhaust
Load
15

Figure 1

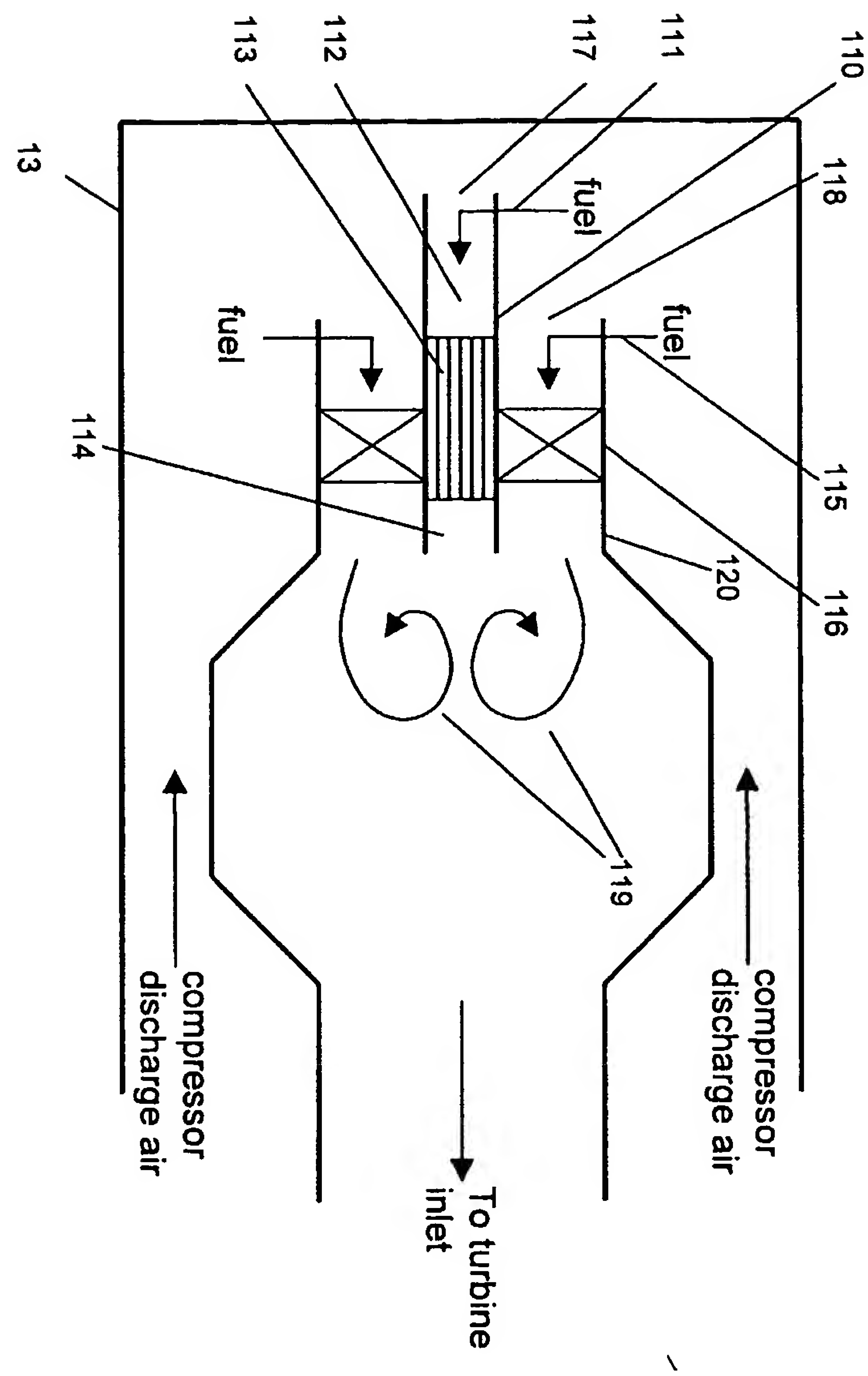

110
111
117
112
113
118
13
fuel
fuel
fuel
114
115
116
120
119
compressor discharge air
compressor discharge air
To turbine inlet

Figure 2

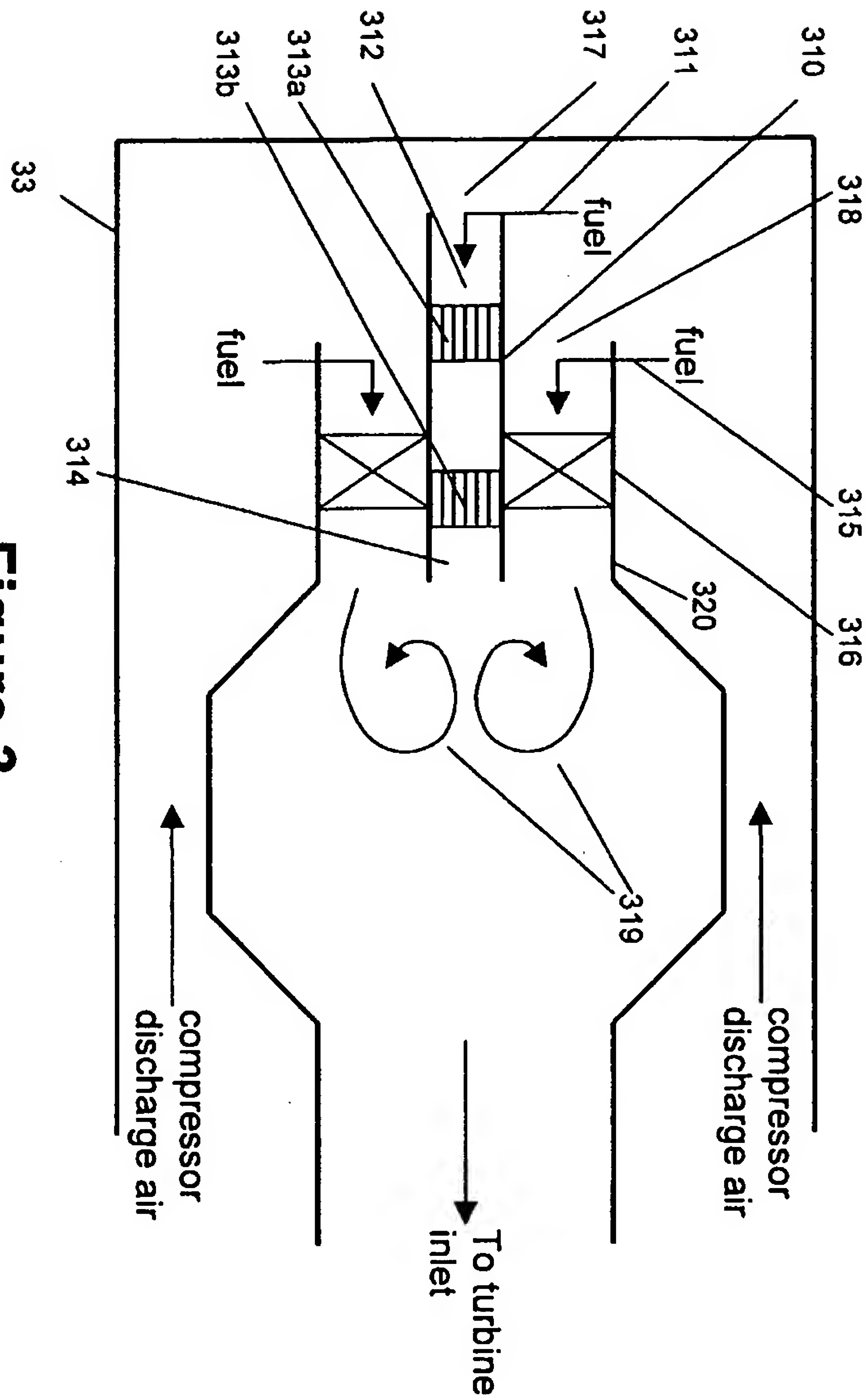

310
311
317
312
313a
313b
318
fuel
fuel
fuel
315
316
320
314
319
33
compressor discharge air
compressor discharge air
To turbine inlet

Figure 3

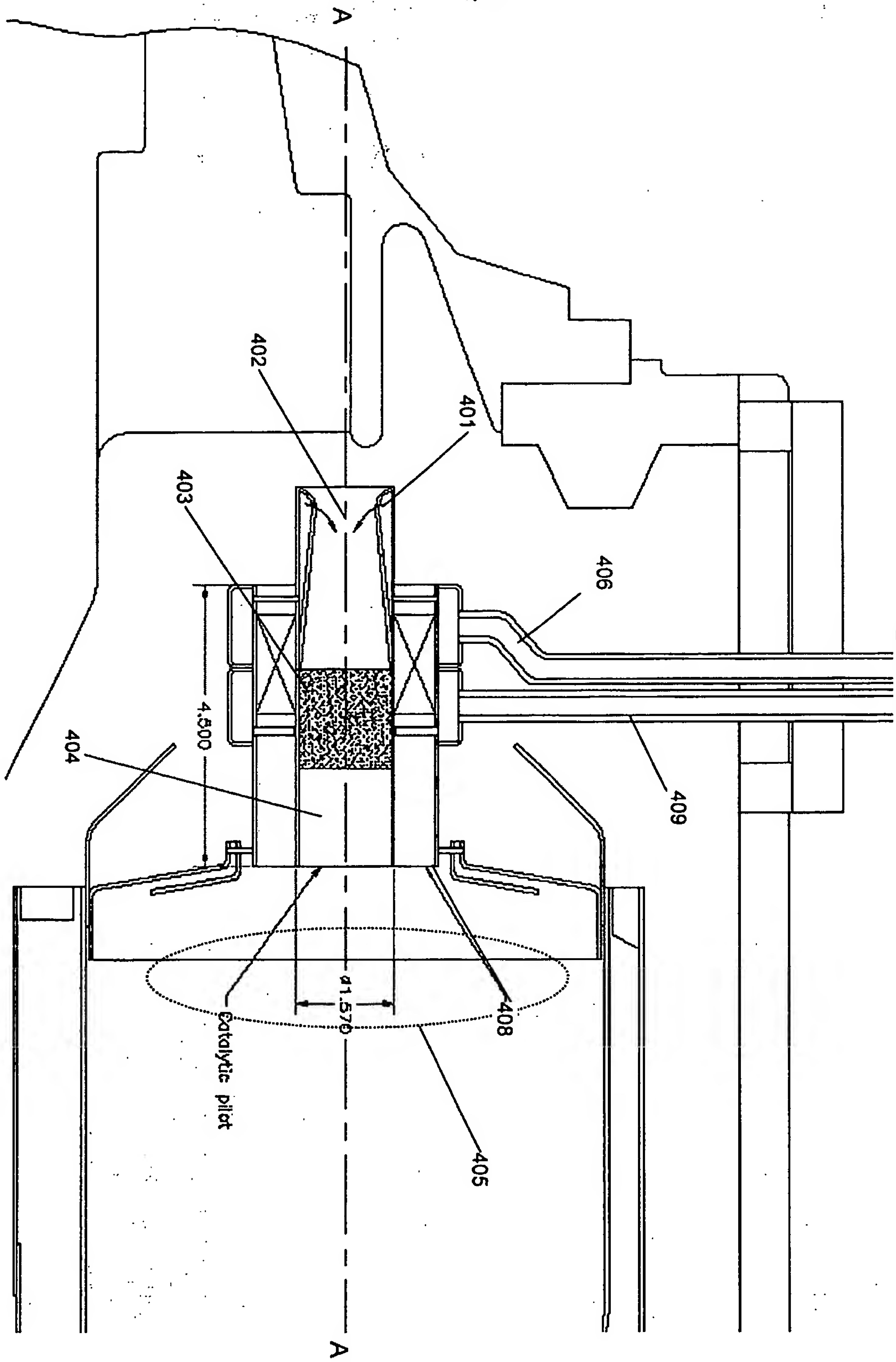
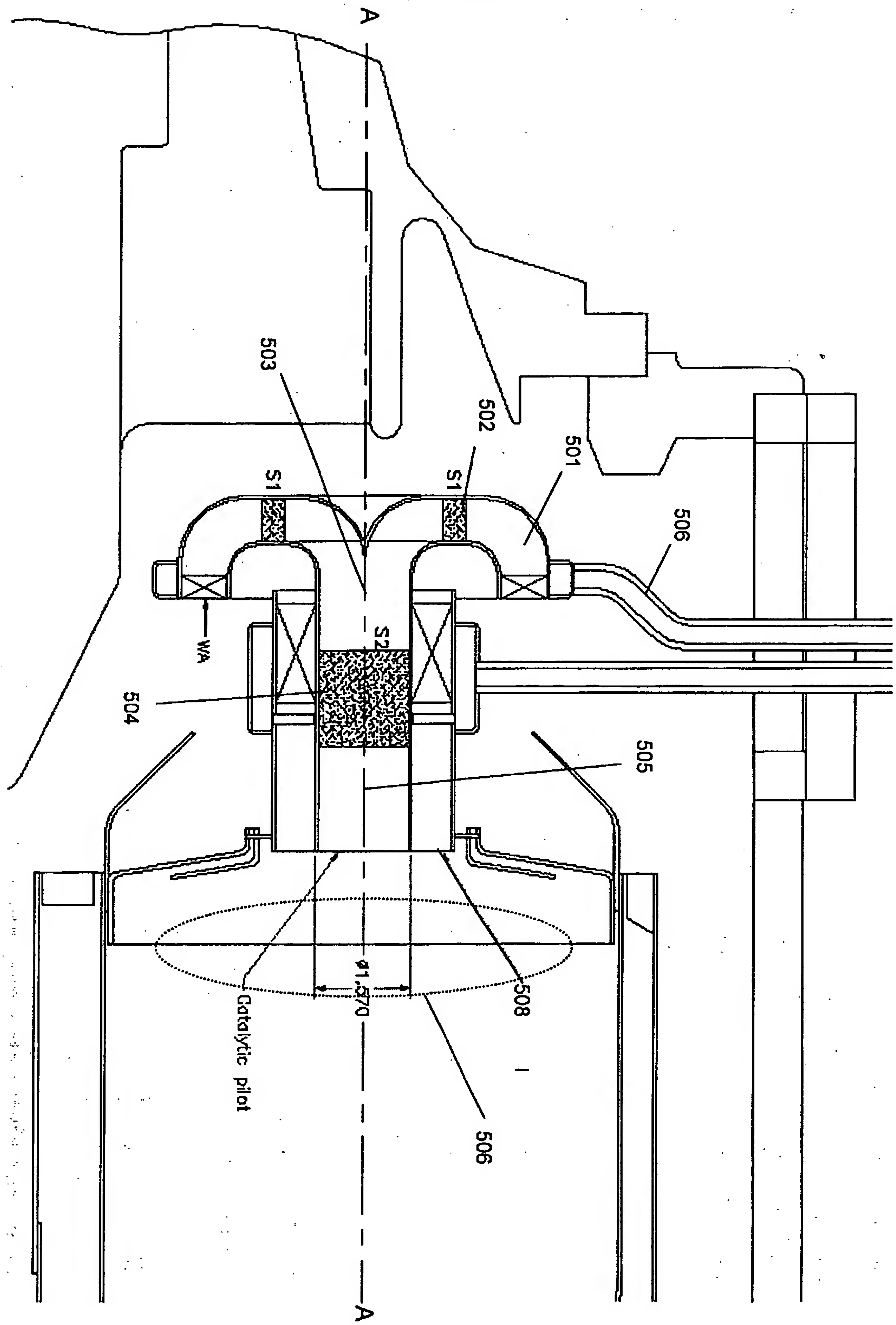


Figure 4



A
503
502
501
S1
S1
506
S2
WA
504
505
508
ø1.570
Catalytic pilot
506
A

Figure 5

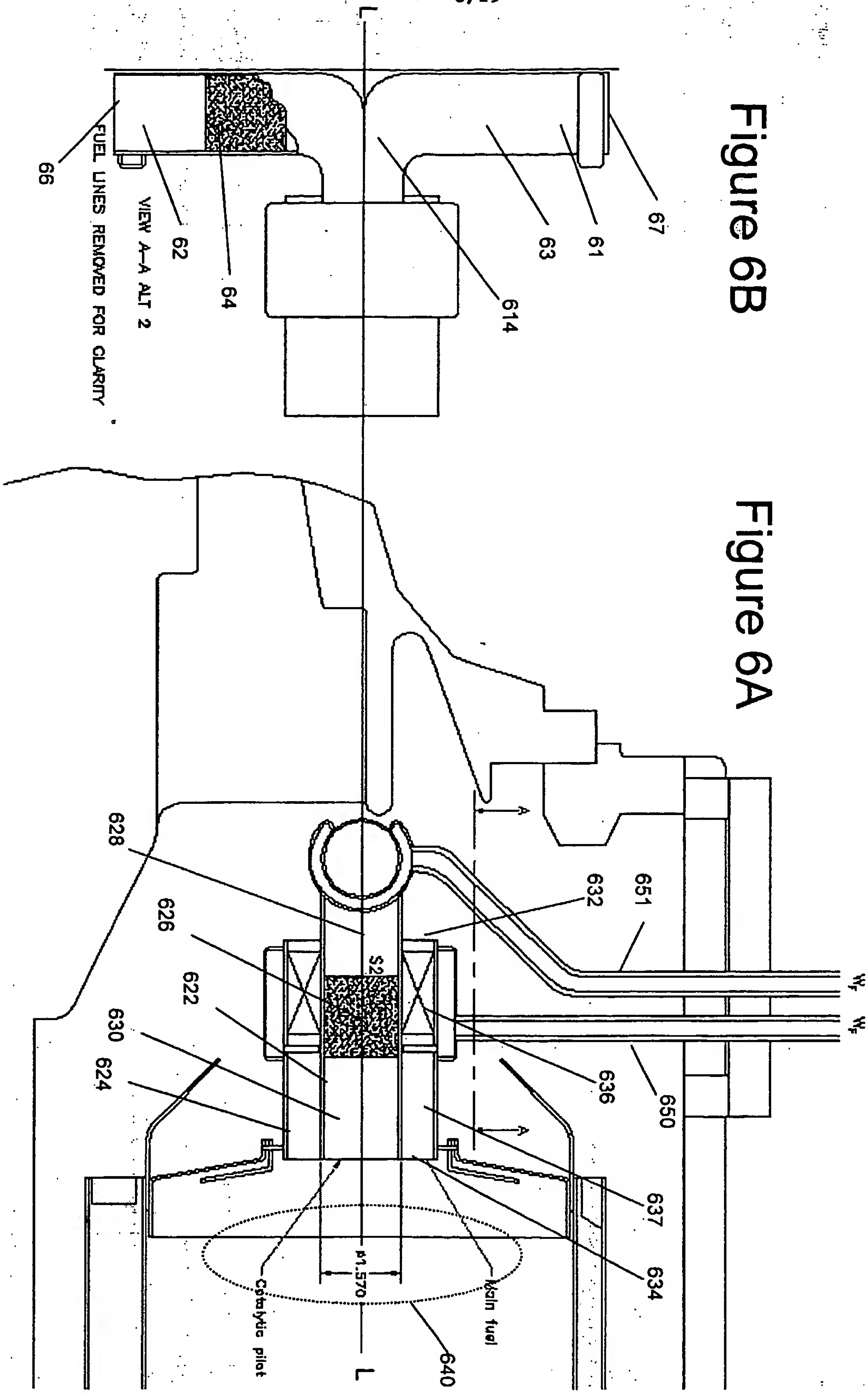


Figure 6B

Figure 6A

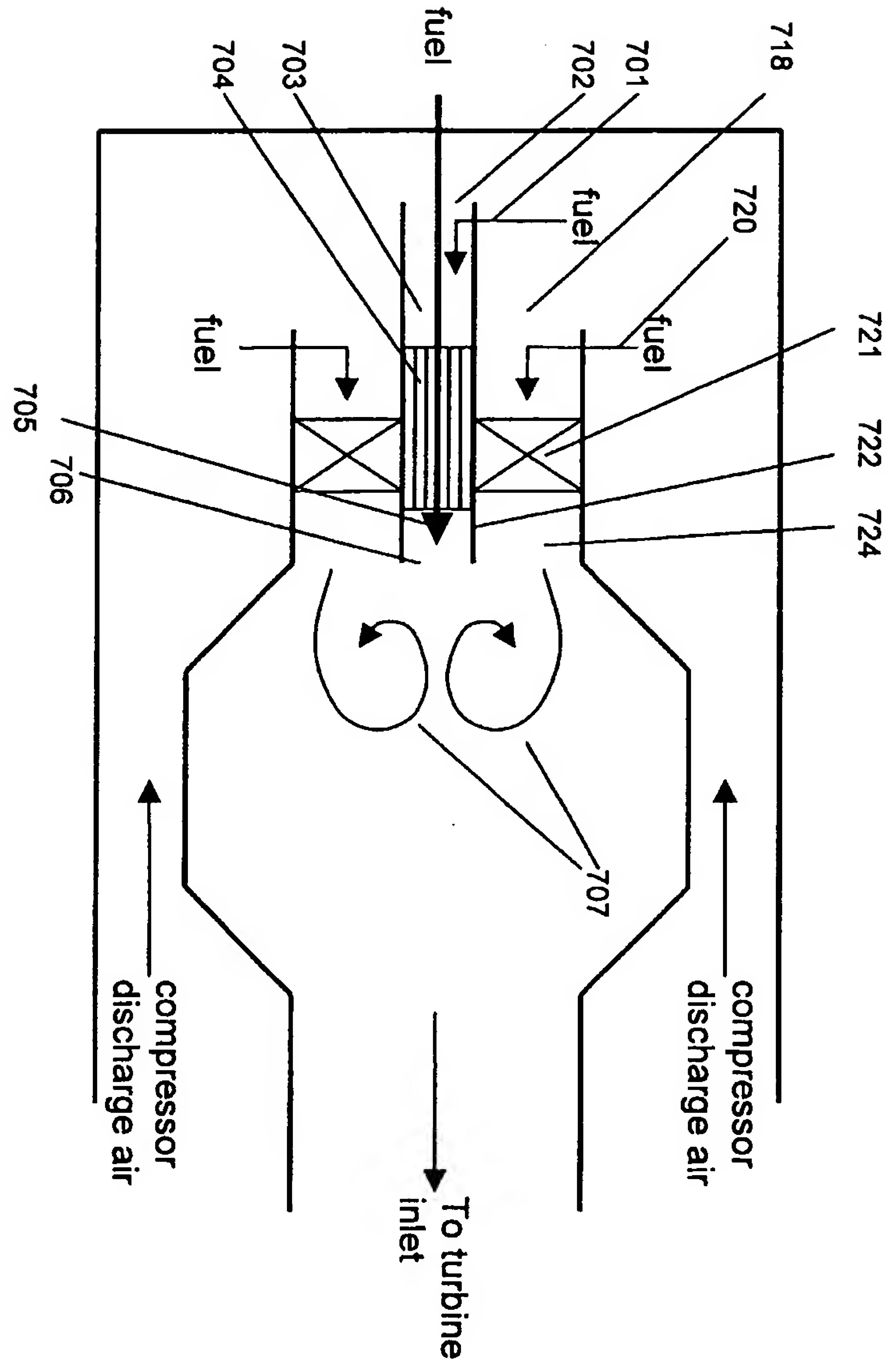

fuel
fuel
fuel
fuel
701
702
703
704
705
706
707
718
720
721
722
724
compressor discharge air
compressor discharge air
To turbine inlet

Figure 7

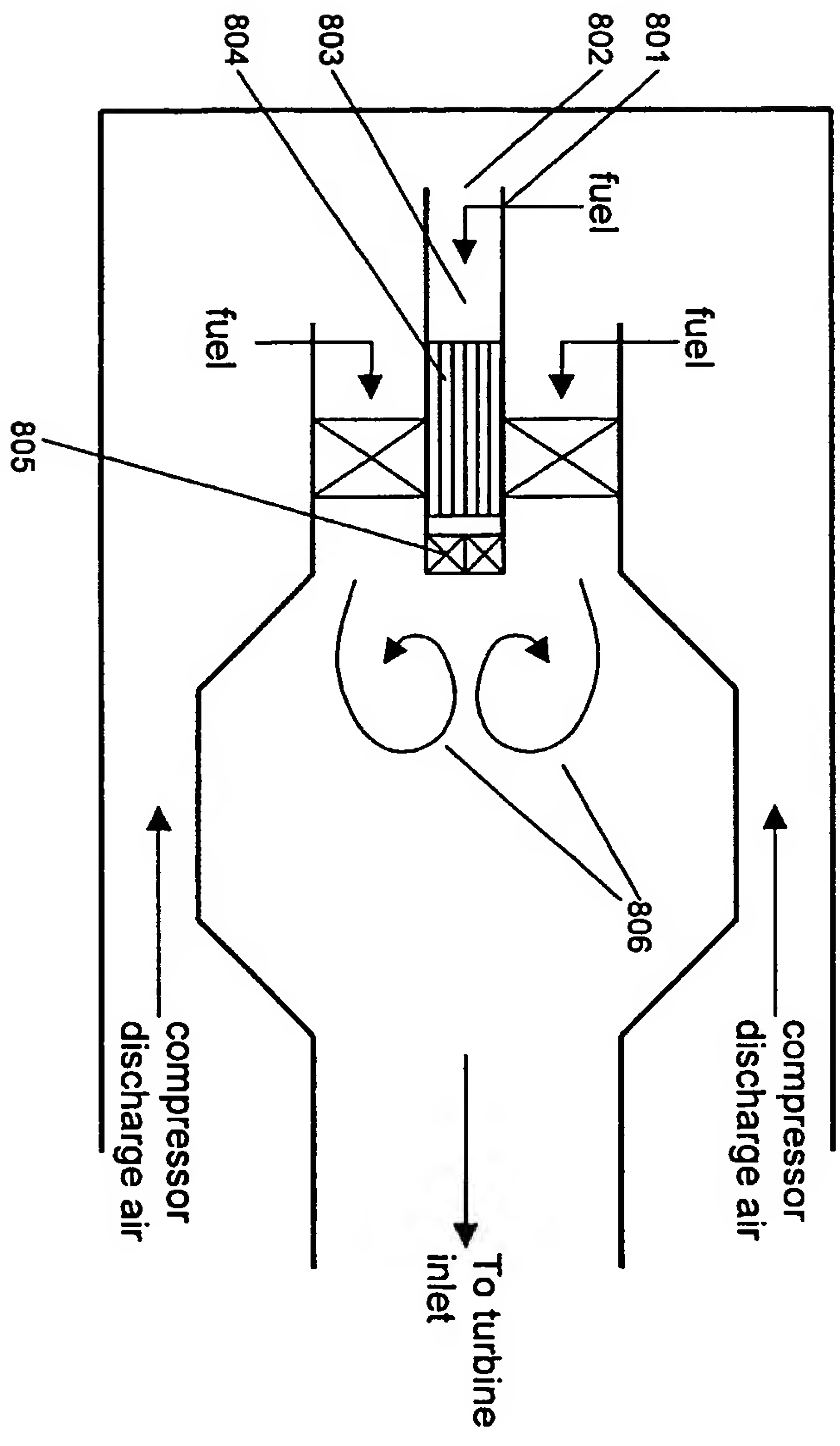

801
802
803
804
805
806
fuel
fuel
fuel
compressor discharge air
compressor discharge air
To turbine inlet

Figure 8

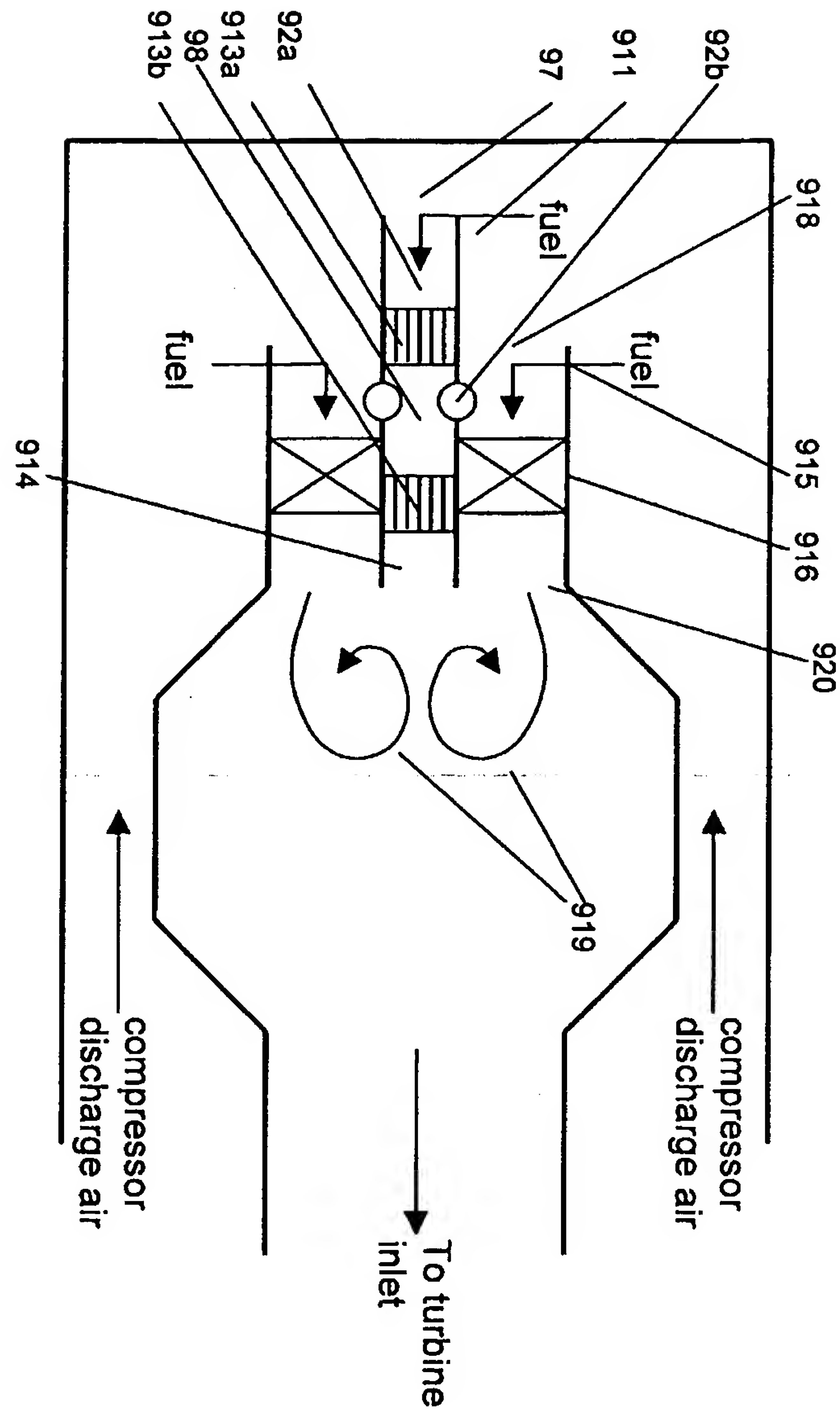

92b
911
97
92a
913a
98
913b
fuel
918
fuel
fuel
914
915
916
920
919
compressor discharge air
compressor discharge air
To turbine inlet

Figure 9

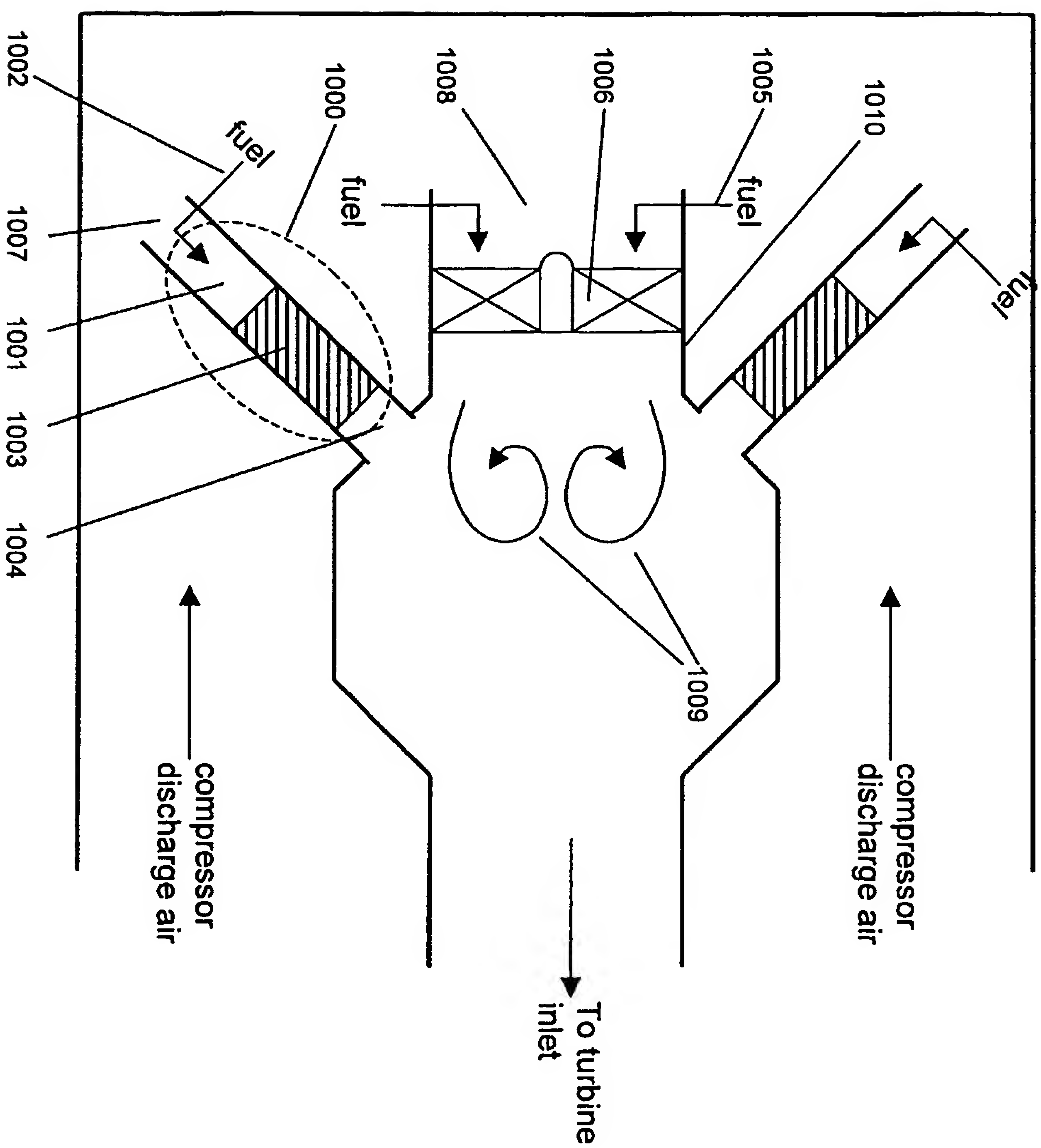
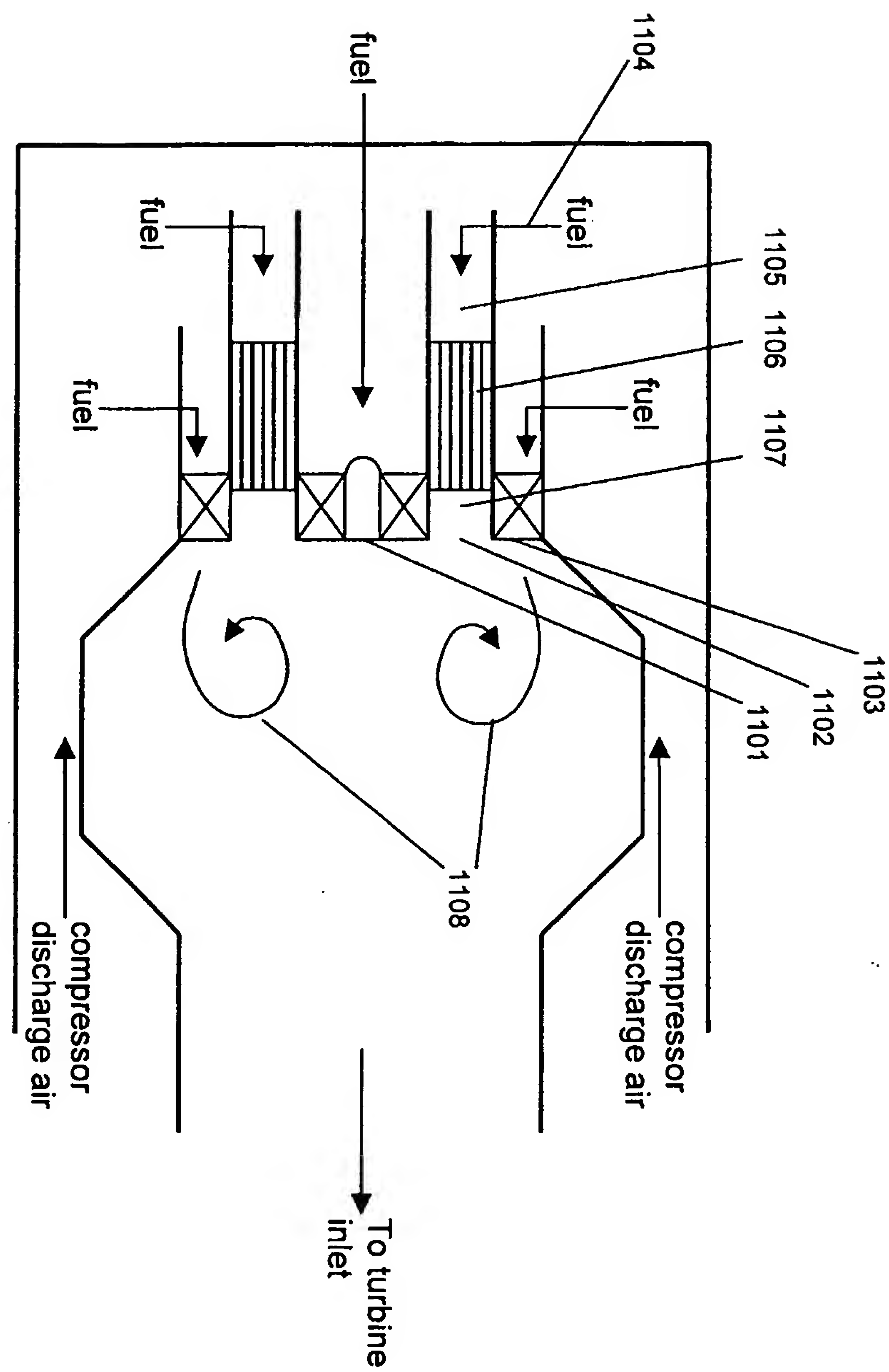

1002
1000
1008
1006
1005
1010
fuel
fuel
fuel
fuel
1007
1001
1003
1004
1009
compressor discharge air
compressor discharge air
To turbine inlet

Figure 10

Figure 11


1104
fuel
fuel
fuel
1105
1106
fuel
fuel
1107
1103
1102
1101
1108
compressor
discharge air
compressor
discharge air
To turbine
inlet

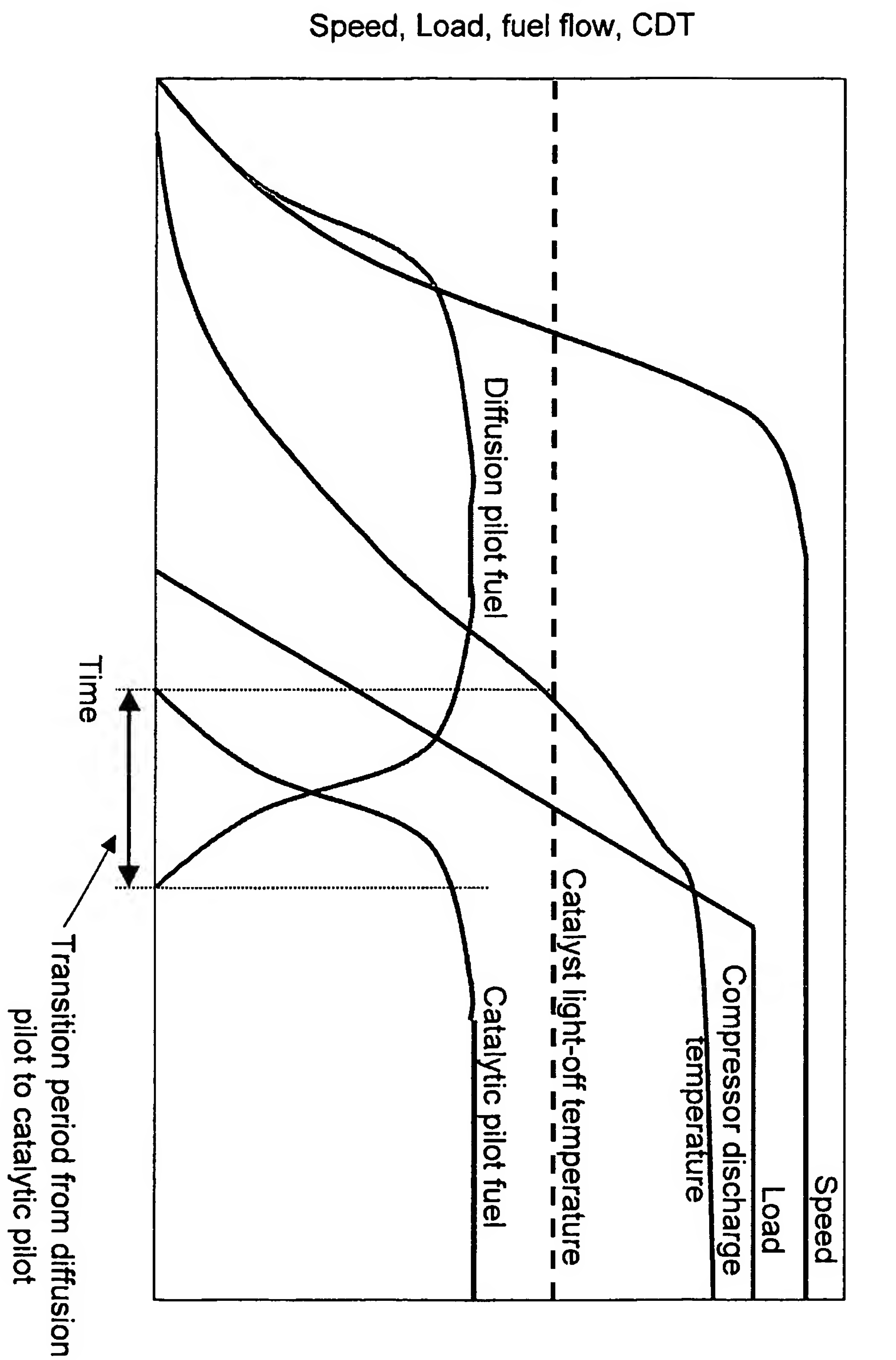

Speed, Load, fuel flow, CDT
Diffusion pilot fuel
Time
Catalyst light-off temperature
Compressor discharge temperature
Load
Speed
Catalytic pilot fuel
Transition period from diffusion pilot to catalytic pilot

Figure 12

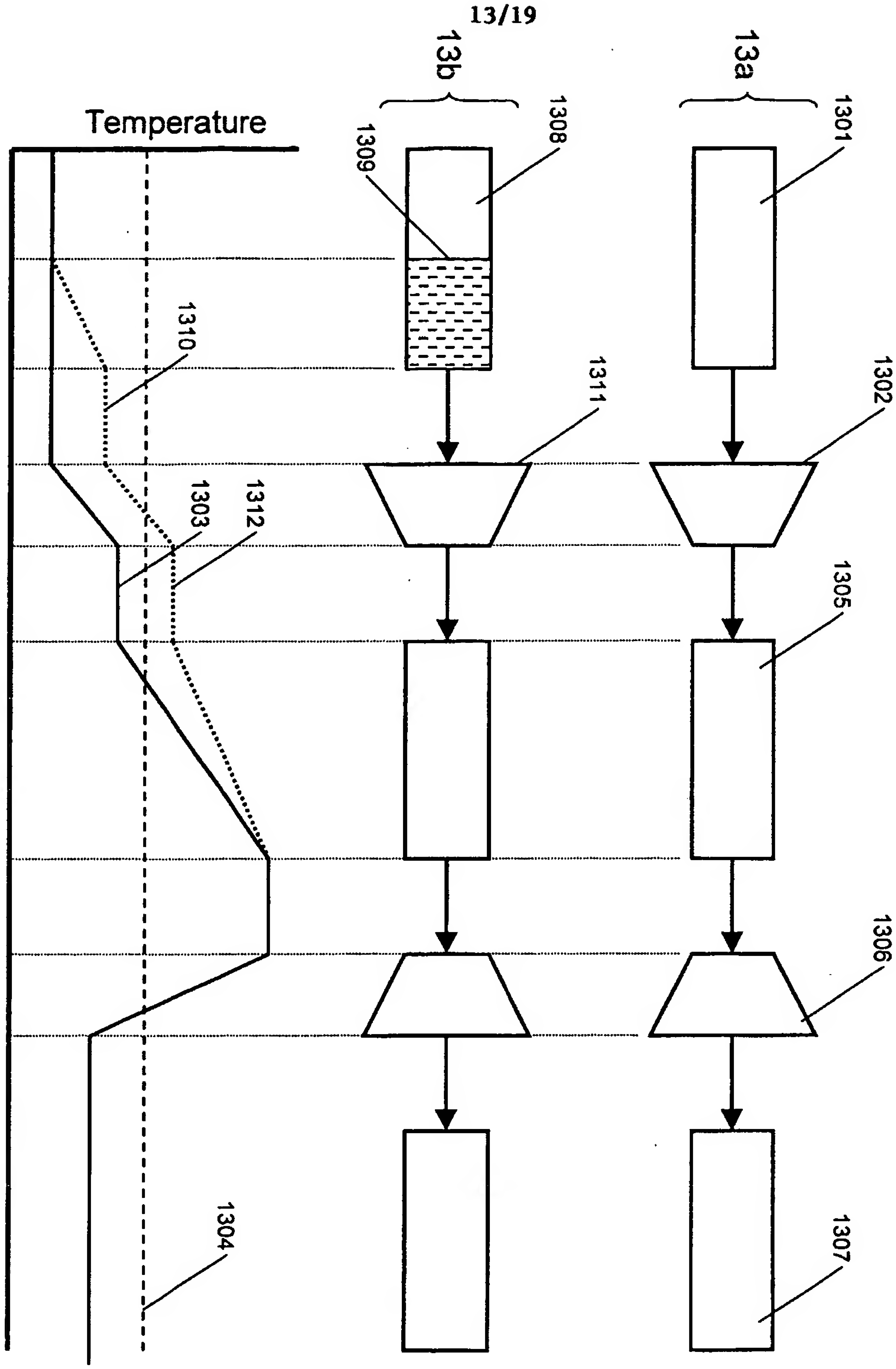

13a
13b
Temperature
1301
1302
1303
1304
1305
1306
1307
1308
1309
1310
1311
1312

Figure 13

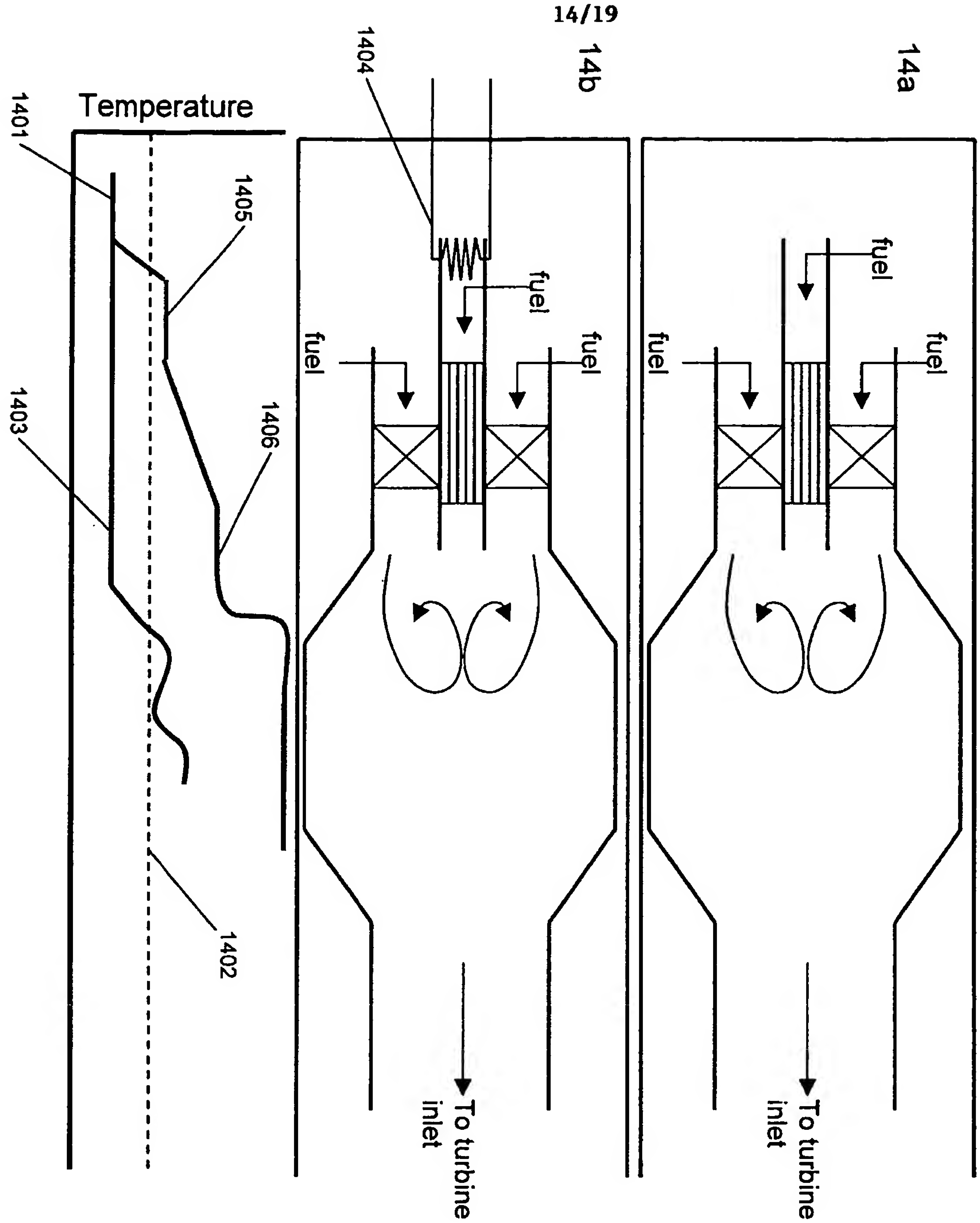

14b
14a
1404
Temperature
1401
1405
1403
1406
1402
fuel
fuel
fuel
fuel
fuel
fuel
To turbine inlet
To turbine inlet

Figure 14

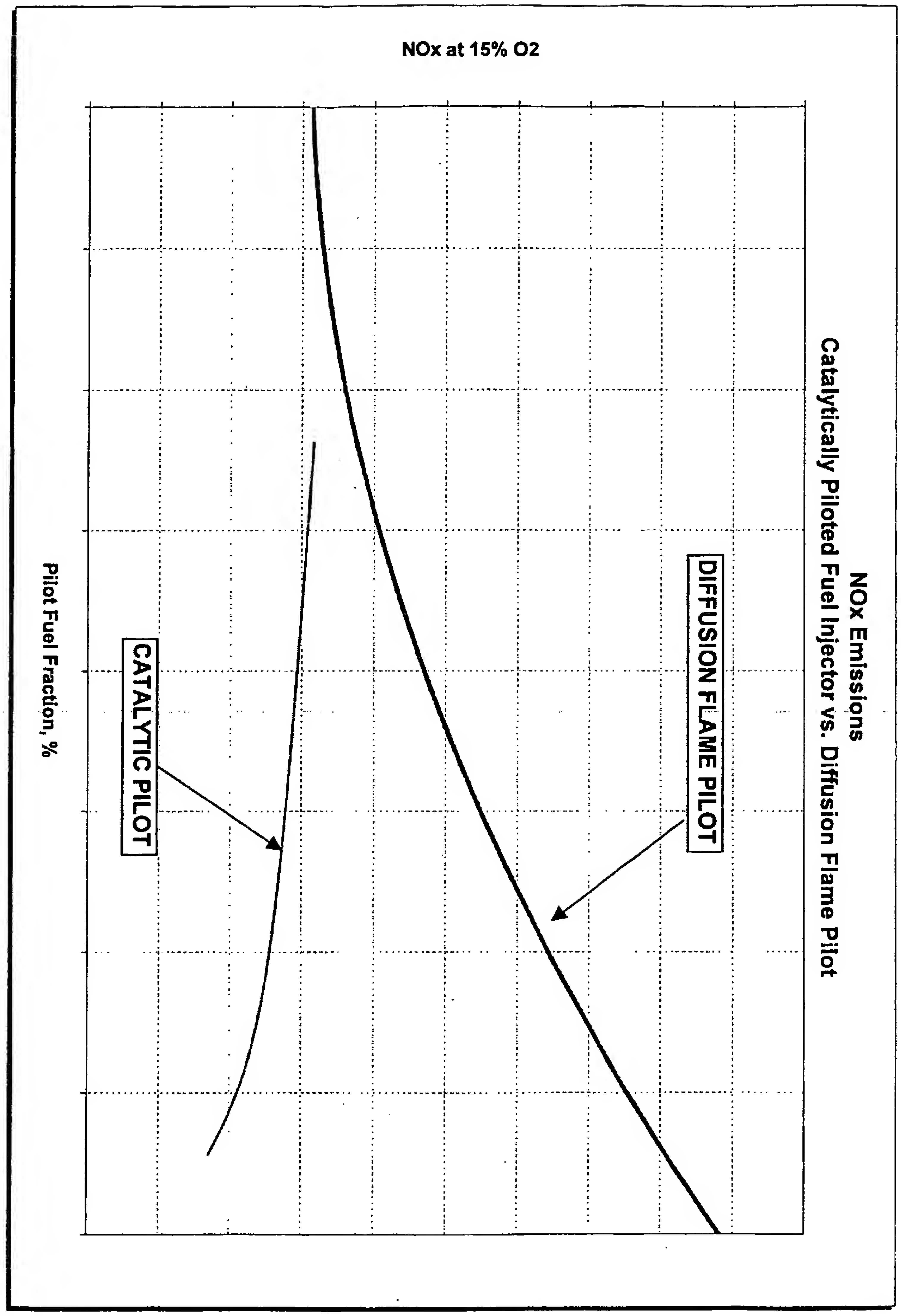

NOx Emissions
Catalytically Piloted Fuel Injector vs. Diffusion Flame Pilot
NOx at 15% O2
Pilot Fuel Fraction, %
DIFFUSION FLAME PILOT
CATALYTIC PILOT

Figure 15

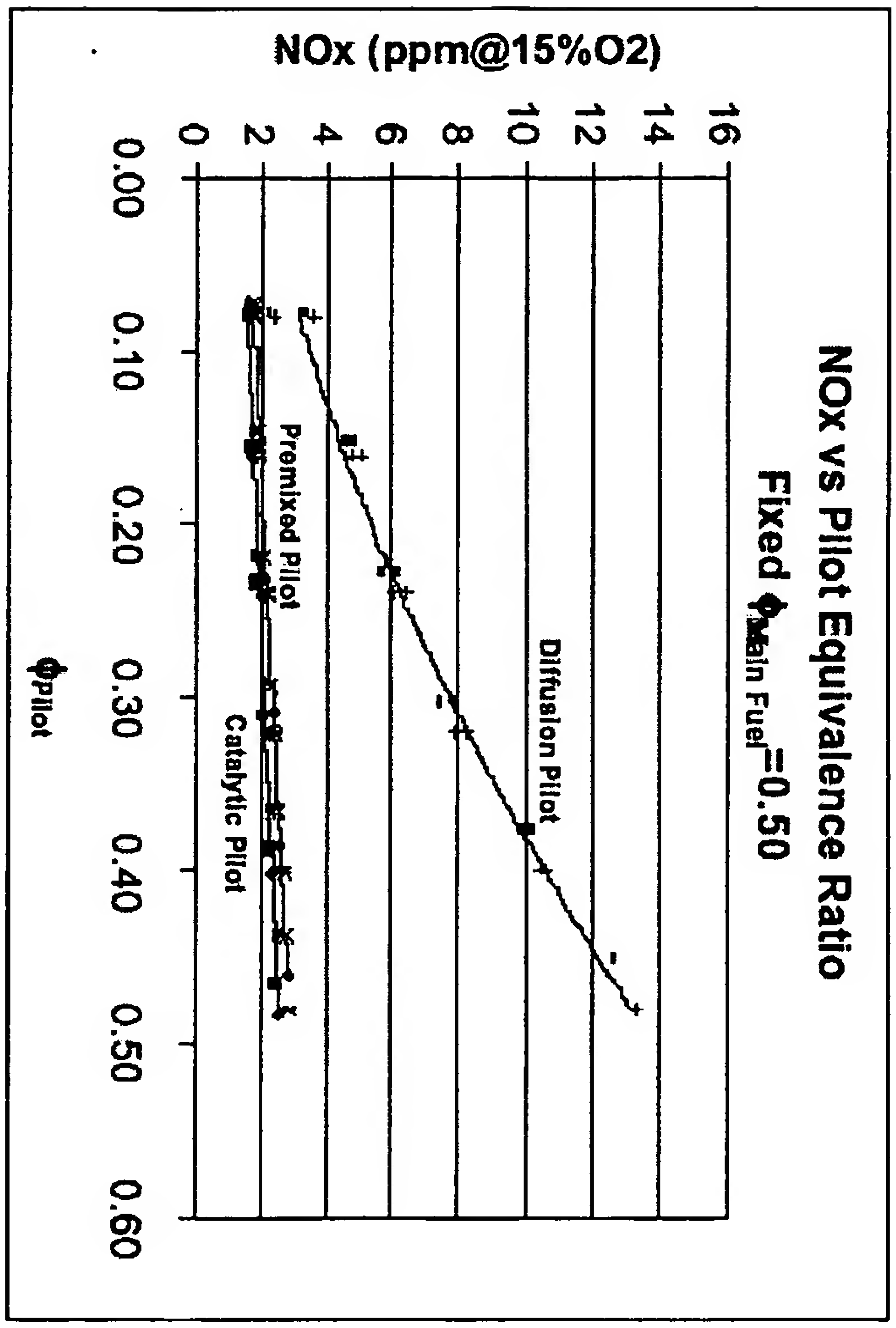

NOx vs Pilot Equivalence Ratio
Fixed Φ Main Fuel=0.50
NOx (ppm@15%O2)
0
2
4
6
8
10
12
14
16
0.00
0.10
0.20
0.30
0.40
0.50
0.60
Φ Pilot
Diffusion Pilot
Premixed Pilot
Catalytic Pilot

Figure 16

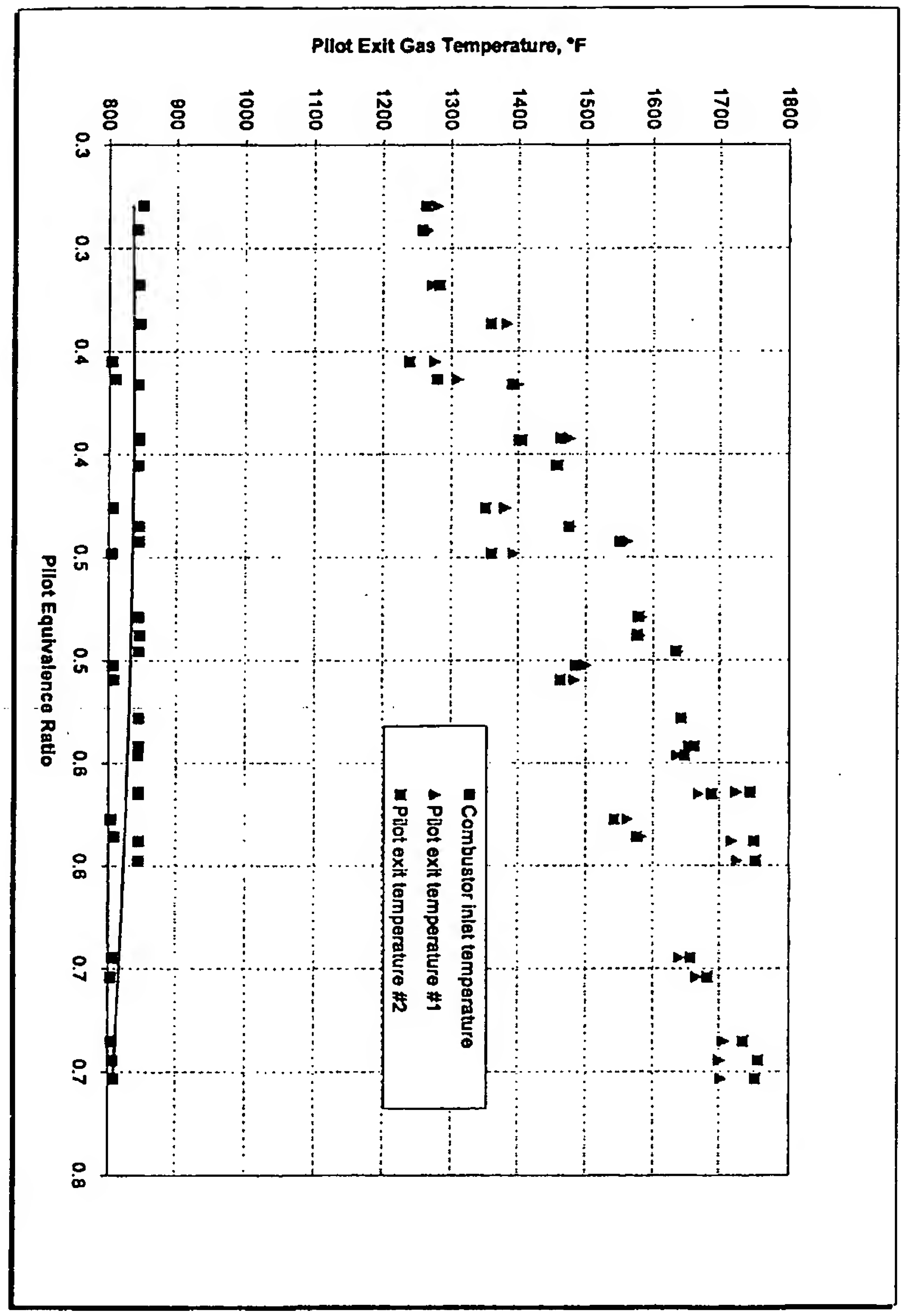

Pilot Exit Gas Temperature, °F
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
0.3
0.3
0.4
0.4
0.5
0.5
0.6
0.6
0.7
0.7
0.8
Pilot Equivalence Ratio
Combustor inlet temperature
Pilot exit temperature #1
Pilot exit temperature #2

Figure 17

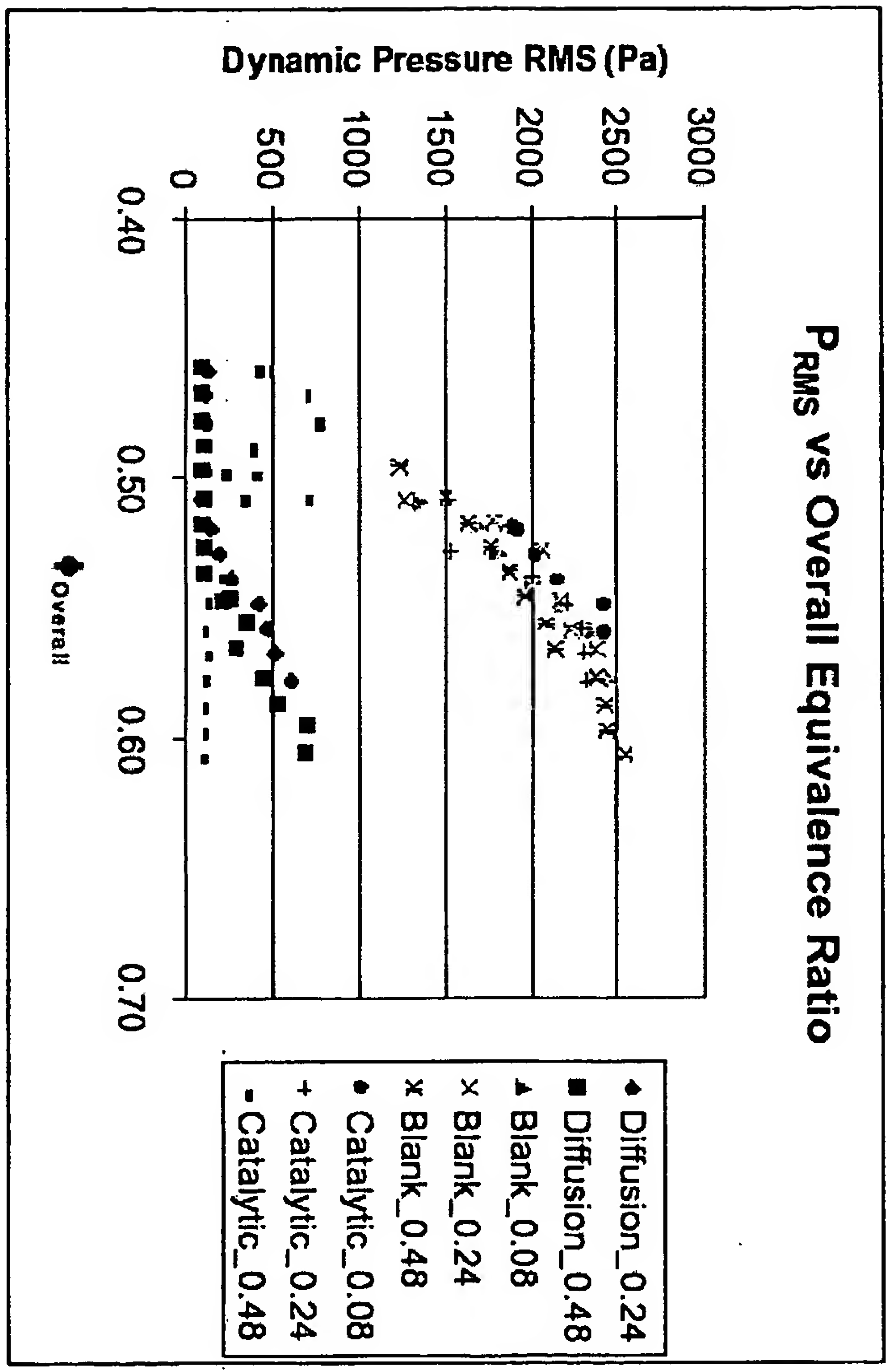

PRMS vs Overall Equivalence Ratio
Dynamic Pressure RMS (Pa)
3000
2500
2000
1500
1000
500
0
0.40
0.50
0.60
0.70
Overall
Diffusion_0.24
Diffusion_0.48
Blank_0.08
Blank_0.24
Blank_0.48
Catalytic_0.08
Catalytic_0.24
Catalytic_0.48

Figure 18

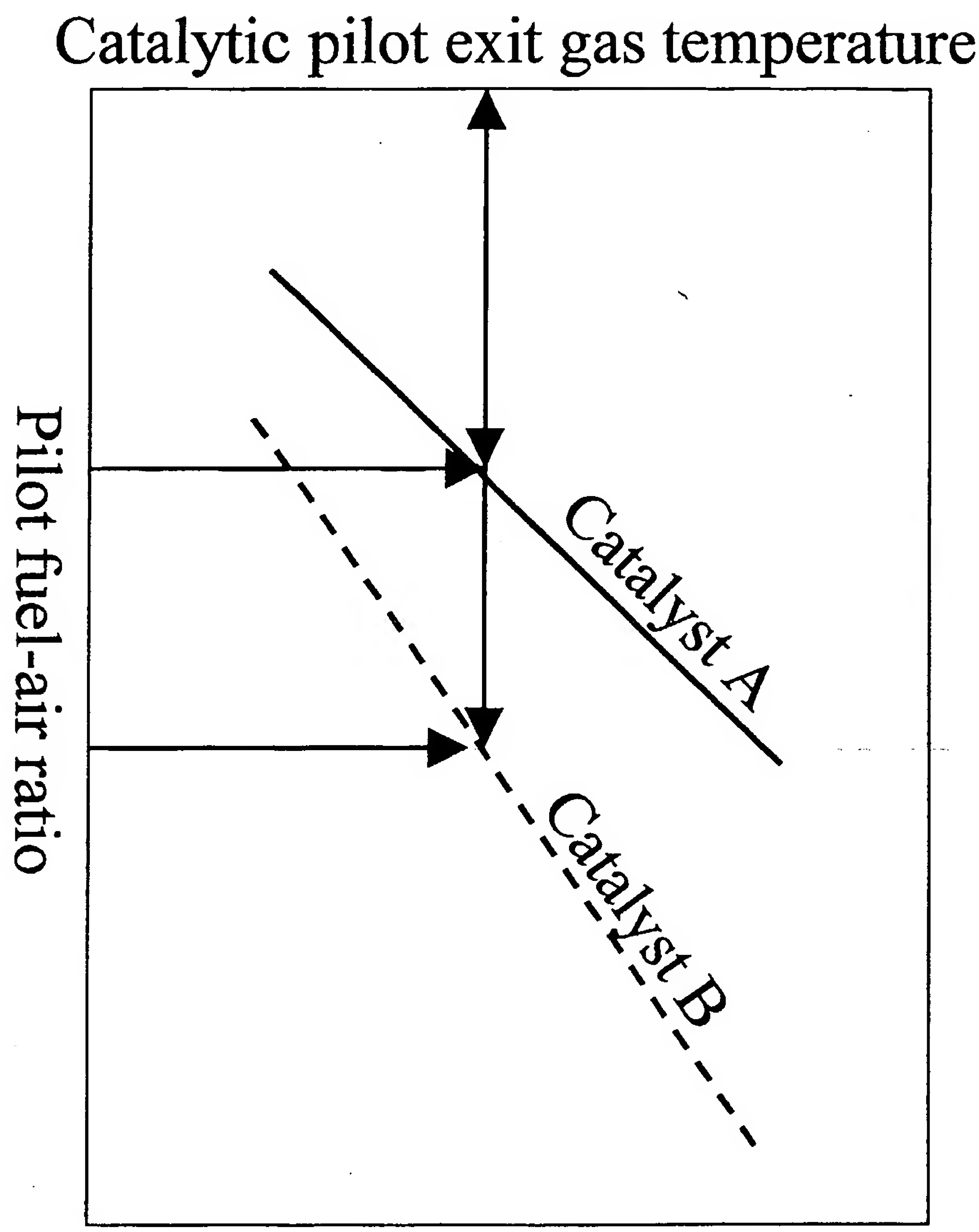

Catalytic pilot exit gas temperature
Pilot fuel-air ratio
Catalyst A
Catalyst B

Figure 19

INTERNATIONAL SEARCH REPORT	International application No. PCT/US03/05312

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : F02C 7/26, 1/00
US CL : 60/77, 723

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 60/77, 723, 737, 747, 748

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 6,237,343 B1 (BUTLER) 29 May 2001 (29.05.2001), see Fig. 2.	1-72
A	US 5,950,434 A (HUMS et al) 14 September 1999 (14.09.1999), see entire document.	1-72
A	US 5,623,819 A (BOWKER et al) 29 April 1997 (29.04.1997), see entire document.	1-72

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 June 2003 (26.06.2003)	16 JUL 2003
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450 Alexandria, Virginia 22313-1450 Facsimile No. (703)305-3230	Authorized officer Charles G Freay Telephone No. (703)308-0861